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QNET Rotary Inverted Pendulum Trainer for NI ELVIS

Developed by Quanser

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1 INTRODUCTION

Regulation and servo problems are very common, but feedback can be used in many other useful ways. The name task-based control is used as a common classification of a wide variety of problems. For instance, stabilization of an unstable system can be considered a task-based problem. However, it is a borderline example since it can also be viewed as a regulation problem. The Segway transporter is a typical example where stabilization is a key task. In that case stabilization is also merged with the steering functions. Other examples are damping of a swinging load on a crane, stabilization of a rocket during take-off, and the human posturing systems. There are many examples of task-based control in aerospace such as automatic landing and orbit transfer of satellites. Robotics is a rich field for task-based control with challenges such as collision avoidance, motion planning, and vision based control. Task-based control is typically more complicated than regulation and servoing but they may contain servo and regulation functions as sub-tasks. We have chosen the rotary pendulum system to illustrate task-based control

The QNET rotary inverted pendulum trainer is shown in Figure 1.1. The motor is mounted vertically in a metal chamber. An L-shaped arm is connected to the motor shaft and pivots between ± 180 degrees. A pendulum is suspended on a horizontal axis at the end of the arm. The pendulum angle is measured by an encoder. The control variable is the input voltage to the pulse-width modulated amplifier that drives the motor. The output variables are the angle of the pendulum and the angle of the motor.

Figure 1.1: QNET rotary inverted pendulum trainer (ROTPENT)

There are three experiments: simple modeling, inverted pendulum balance control, and swing-up control. The experiments can be performed independently.

Topics Covered

- Modeling the pendulum
- Balance control (via state-feedback)

- Control optimization (LQR)
- Friction compensation
- Energy control
- Hybrid control

Prerequisites
In order to successfully carry out this laboratory, the user should be familiar with the following:

- Transfer function fundamentals, e.g. obtaining a transfer function from a differential equation.
- Using LabVIEW® to run VIs.

2 SIMPLE MODELING

2.1 Background

This experiment illustrates some control tasks for gantry cranes. The gantry is a moving platform or trolley that transports the crane about the factory floor or harbor. The load hangs from the crane using wires and is moved by the gantry crane. Typically the problem is to move the load quickly and move it to the correct position. The fast motion necessary for production makes it more difficult to move the load to the correct location given the swinging motions of the crane. This problem can be mimicked using the rotary pendulum system by viewing the tip of the L-shaped arm as the moving trolley and the pendulum tip as the load being carried.

In this experiment we will begin by modeling the system and determine strategies to dampen the oscillations of the system.

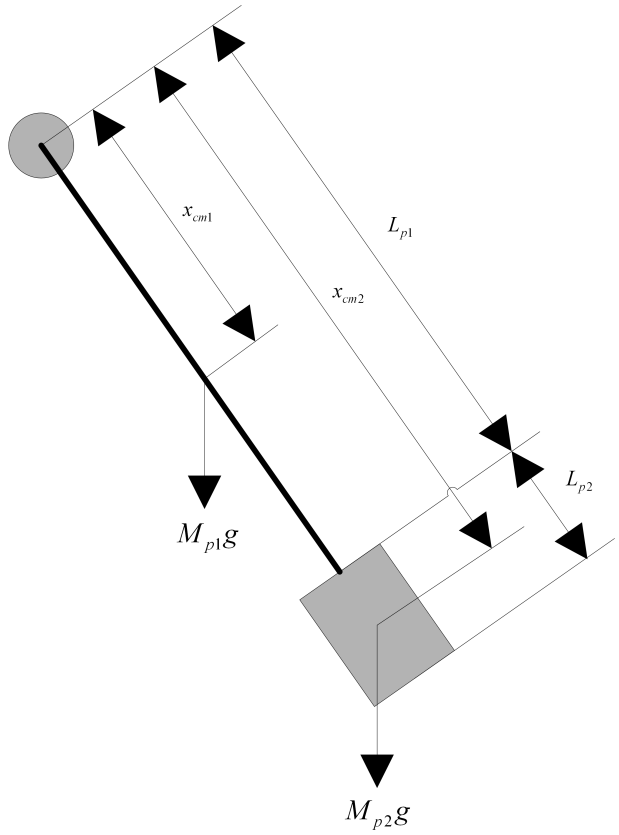


Figure 2.1: Free-body diagrams of pendulum assembly

Figure 2.1 shows the free-body diagram of the pendulum assembly that is composed of two rigid bodies: the pendulum link with mass M_{p1} and length L_{p1}, and the pendulum weight with mass M_{p2} and a length L_{p2}. The center of mass of the the pendulum link and the pendulum weight are calculated separately using the general expression

$$x_{cm} = \frac{\int p\, x\, dx}{\int p\, dx}$$

where x is the linear distance from the pivot axis and p is the density of the body. The circle in the top-left corner of Figure 2.1 represents the axis of rotation or the pivot axis that goes into the page.

The pendulum system is then expressed as one rigid body with a single center of mass, as shown in Figure 2.2.

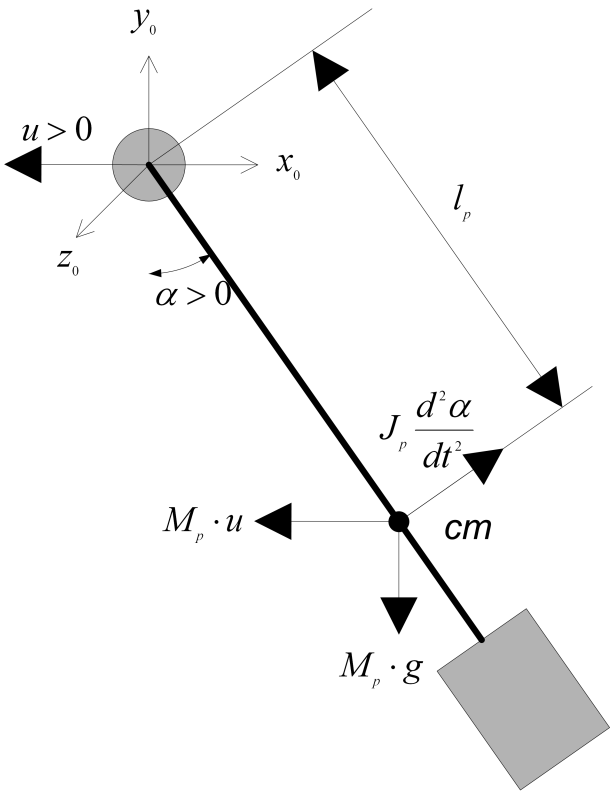


Figure 2.2: Free-body diagram of composite pendulum

The center of mass of a composite object that contains n bodies can be calculated using

$$x_{cm} = \frac{\sum_{i=1}^{n} m_i x_{cm,i}}{\sum_{i=1}^{n} m_i}$$

where $x_{cm,i}$ is the known center of mass of body i and m_i is the mass of body i.

From the free-body diagram in Figure 2.2, the resulting nonlinear equation of motion of the pendulum is

$$J_p \ddot{\alpha}(t) = M_p \, g \, l_p \sin \alpha(t) + M_p \, u \, l_p \cos \alpha(t) \tag{2.1}$$

where J_p is the moment of inertia of the pendulum at the pivot axis z_0, M_p is the total mass of the pendulum assembly, u is the linear acceleration of the pivot axis, and l_p is the center of mass position as depicted in Figure 2.2. Thus as the pivot accelerates towards the left the inertia of the pendulum causes it to swing upwards while the gravitation force $M_p g$ and the applied force $M_p u$ (the left-hand terms in Equation 2.1) pull the pendulum downwards.

The moment of inertia of the pendulum can be found experimentally. Assuming the pendulum is unactuated, linearizing Equation 2.1 and solving for the differential equation gives the expression

$$J_p = \frac{M_p \, g \, l_p}{4 f^2 \pi^2} \tag{2.2}$$

where f is the measured frequency of the pendulum as the arm remains rigid. The frequency is calculated using

$$f = \frac{n_{cyc}}{\Delta t} \tag{2.3}$$

where n_{cyc} is the number of cycles and Δt is the duration of these cycles. Alternatively, J_p can be calculated using the moment of inertia expression

$$J = \int r^2 dm \tag{2.4}$$

where r is the perpendicular distance between the element mass, dm, and the axis of rotation.

In addition to finding the moment of inertia, this laboratory investigates the stiction that is present in the system. The rotor of the DC motor that moves the ROTPEN system requires a certain amount of current to begin moving. In addition, the mass from the pendulum system requires even more current to actually begin moving the system. The friction is particularly severe for velocities around zero because friction changes sign with the direction of rotation.

See Wikipedia for more information on: center of mass, inertia, pendulum, and friction.

2.2 Simple Modeling Virtual Instrument

The virtual instrument for studying the physics of the pendulum when in the gantry configuration is shown in Figure 2.3.

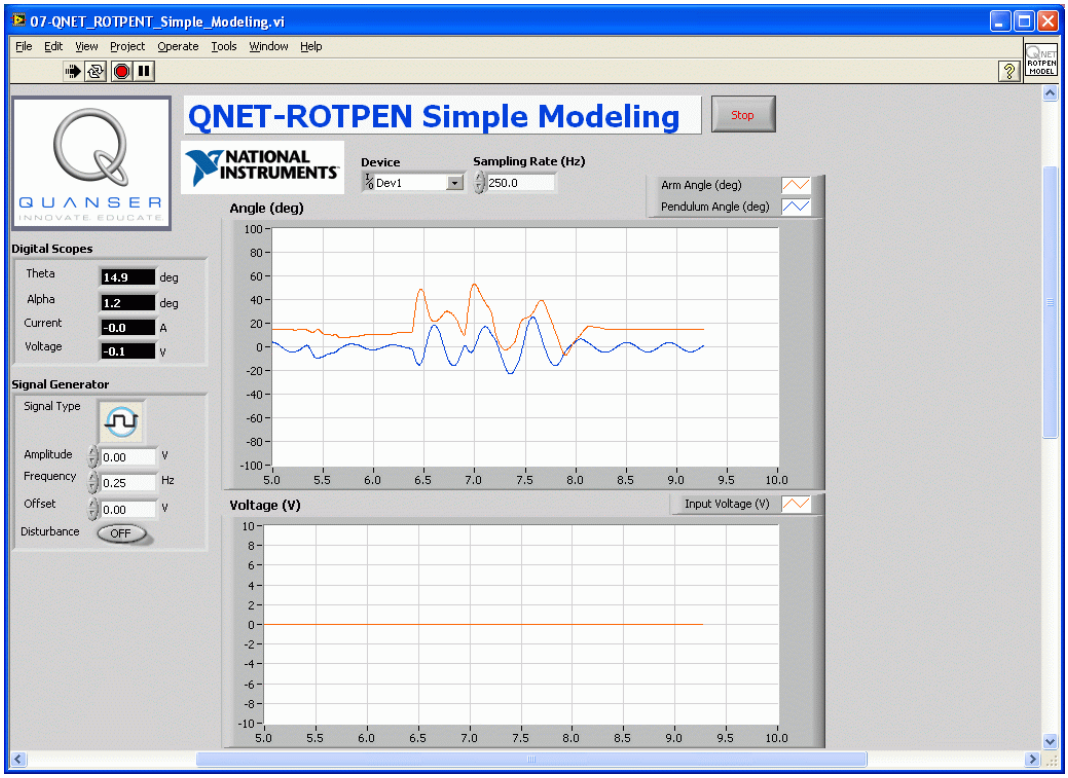


Figure 2.3: LabVIEW VI for modeling QNET rotary pendulum.

2.3 Damping [15 min]

1. Ensure the QNET ROTPENT Simple Modeling VI is open and configured as described in Section 2.2. **Make sure the correct *Device* is chosen.**
2. Run the QNET_ROTPENT_Simple_Modeling.vi shown in Figure 2.3.
3. Hold the arm of the rotary pendulum system stationary and manually perturb the pendulum.
4. While still holding the arm, examine the response of *Pendulum Angle (deg)* in the *Angle (deg)* scope. This is the response from the **pendulum** system.
5. Repeat 3 above but release the arm after several swings.

6. B-5, B-7 Examine the *Pendulum Angle (deg)* response when the arm is not fixed. This is the response from the **rotary pendulum** system. Given the response from the **pendulum** and **rotary pendulum** system, which converges faster towards angle zero? Why does one system dampen faster than the other?

Answer 2.1

Outcome	Solution
B-5	If the procedure was followed correctly, they should be able to draw some conclusions based on examined responses.
B-7	The rotary pendulum system converges to angle zero more rapidly. The rotary pendulum system is naturally more damped due to the coupling effect between the rotary arm and pendulum link.

□□□

7. Stop the VI by clicking on the *Stop* button.

2.4 Friction [15 min]

1. Run the QNET_ROTPENT_Simple_Modeling.vi.
2. In the *Signal Generator* section set
   - Amplitude = 0 V
   - Frequency = 0.25 Hz
   - Offset = 0.0 V
3. Change the *Offset* in steps of 0.10 V until the pendulum begins moving. Record the voltage at which the pendulum moved.
4. Repeat Step 3 above for steps of -0.10 V.
5. B-5, B-7 Enter the positive, V_{fp}, and negative voltage, V_{fn}, values needed to get the pendulum moving. Why does the motor need a certain amount of voltage to get the motor shaft moving?

Answer 2.2

Outcome	Solution
B-5	If the procedure was followed correctly, they should be able to draw some conclusion based on examined responses.
B-7	The positive and negative Coulomb friction voltages recorded are $V_{fp} = 2.1$ V and $V_{fn} = -2.9$ V. These results will vary between QNET ROTPEN systems. To overcome the friction in the motor, a certain amount of current is required to make the rotor move. The amount of voltage in either direction varies between 1.0 V and 3.0 V.

□□□

6. Stop the VI by clicking on the *Stop* button.

2.5 Moment of Inertia [30 min]

2.5.1 Pre-Lab Questions

1. A-1, A-2 Find the moment of inertia acting about the pendulum pivot using the free-body diagram. Make sure you evaluate numerically using the parameters defined in the QNET ROTPEN User Manual ([2]).

Answer 2.3

Outcome	Solution
A-1	Use Equation 2.4 with the pendulum free-body diagram given in Figure 2.1 to find its moment of inertia.
A-2	Using Equation 2.4 on the FBD in Figure 2.1

$$\begin{aligned} J_p &= p_1 \int_0^{L_{p1}} r^2 dr + p_2 \int_{L_{p1}}^{L_{p1}+L_{p2}} r^2 dr \\ &= \frac{1}{3} M_{p1} L_{p1}^2 + M_{p2} L_{p1}^2 + M_{p2} L_{p1} L_{p2} + \frac{1}{3} M_{p2} L_{p2}^2. \end{aligned}$$

When evaluated with the pendulum parameters given in the QNET Rotary Pendulum User Manual ([2]),

$$J_p = 6.98 \times 10^{-4} \text{ kg} \cdot \text{m}^2$$

□□□

2.5.2 In-Lab Exercises

1. Run the QNET_ROTPENT_Simple_Modeling.vi.
2. In the *Signal Generator* section set
   - Amplitude = 1.0 V
   - Frequency = 0.25 Hz
   - Offset = 0.0 V
3. Click on the *Disturbance* toggle switch to perturb the pendulum and measure the amount of time it takes for the pendulum to swing back-and-forth in a few cycles (e.g., 4 cycles).
4. B-5, K-1 Find the frequency and moment of inertia of the pendulum using the observed results. See Section 2.1 to see how to calculate the inertia experimentally.

   Answer 2.4

Outcome	Solution
B-5	If they were able to follow the procedure properly, then they should be able to measure the number of cycles.
K-1	After performing the experiment, the pendulum goes through 6 cycles in 2.5 s. Using Equation 2.3, the frequency is

   $$f = \frac{6}{2.5} = 2.4 \text{ Hz}$$

   Substituting this and the pendulum parameters defined in [2] in Equation 2.2,

   $$J_{p,exp} = \frac{0.0270 \times 9.81 \times 0.153}{4 \times 2.4^2 \times \pi^2} = 1.77 \times 10^{-4} \text{ kg} \cdot \text{m}^2$$

   □□□
5. B-9 Compare the moment of inertia calculated analytically in Exercise 1 and the moment of inertia found experimentally. Is there a large discrepancy between them?

Answer 2.5

Outcome	Solution
B-9	The moment of inertia found analytically is 6.98×10^{-4} kg $\cdot$ m^2 while the experimentally determined inertia is 1.77×10^{-4} kg $\cdot$ m^2. This discrepancy may be due to an inaccuracy when measuring the pendulum frequency or the fact that this frequency is the damped frequency (not the undamped natural frequency that the equation to compute the inertia uses).

□□□

6. Stop the VI by clicking on the *Stop* button.

2.6 Results

Fill out Table 1 with your answers from above.

Description	Symbol	Value	Unit
Section 2.4: Friction			
Positive Coulomb Friction Voltage	V_{fp}	2.1	V
Negative Coulomb Friction Voltage	V_{fn}	-2.9	V
Section 2.5: Moment of Inertia			
Calculated inertia	J_p	6.98×10^{-4}	kg $\cdot$ m^2
Experimentally found inertia	$J_{p,exp}$	1.77×10^{-4}	kg $\cdot$ m^2

Table 1: QNET ROTPENT Modeling results summary

3 BALANCE CONTROL DESIGN

3.1 Background

A rich collection of methods for finding parameters of control strategies have been developed. Several of them have also been packaged in tools that are relatively easy to use. Linear Quadratic Regulator (LQR) theory is a technique that is suitable for finding the parameters of the balancing controller in Equation 4.1 in Section 4. Given that the equations of motion of the system can be described in the form

$$\dot{x} = Ax + Bu$$

the LQR algorithm computes a control task, u, to minimize the criterion

$$J = \int_0^\infty x(t)^T Q x(t) + u(t)^T R u(t) dt$$

The matrix Q defines the penalty on the state variable and the matrix R defines the penalty on the control actions. Thus when Q is made larger, the controller must work harder to minimize the cost function and the resulting control gain will be larger. In our case the state vector x is defined

$$x = \begin{bmatrix} \theta & \alpha & \dot{\theta} & \dot{\alpha} \end{bmatrix}^T$$

Since there is only one control variable, R is a scalar and the control strategy used to minimize cost function J is given by

$$u = -K(x - x_r) = -k_{p,\theta}(\theta - \theta_r) - k_{p,\alpha}(\alpha - \pi) - k_{d,\theta}\dot{\theta} - k_{d,\alpha}\dot{\alpha}.$$

The LQR theory has been packaged in the LabVIEW® *Control Design and Simulation Module*. Thus given a model of the system in the form of the state-space matrices A and B and the weighting matrices Q and R, the LQR function in the *Control Design* Toolkit computes the feedback control gain automatically. In this experiment, the model is already available. In the laboratory, the effect of changing the Q weighting matrix while R is fixed to 1 on the cost function J will be explored.

See Wikipedia for more information on optimal control.

3.2 Balance Control Design VI

The QNET_ROTPENT_Control_Design VI has three tabs. Each tab is explained in the following sections.

3.2.1 Symbolic Model Tab

The *Symbolic Model* tab shown in Figure 3.1 is used to setup the QNET rotary pendulum model.

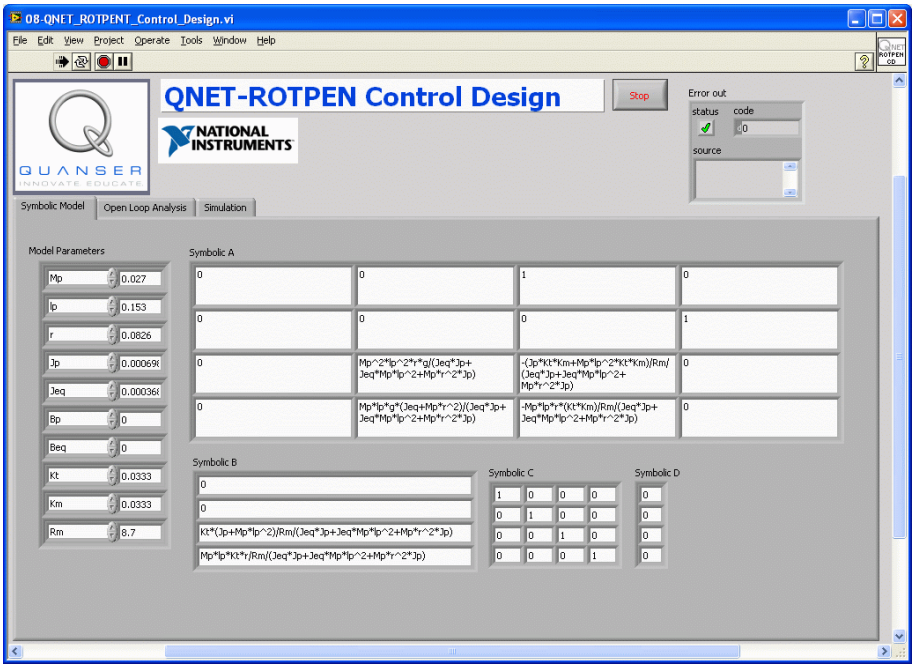


Figure 3.1: LabVIEW VI to generate state-space model of QNET rotary pendulum.

3.2.2 Open Loop Analysis Tab

The *Open Loop Analysis* tab on the VI is used to analyze the open loop stability of the QNET rotary pendulum system, shown in Figure 3.2.

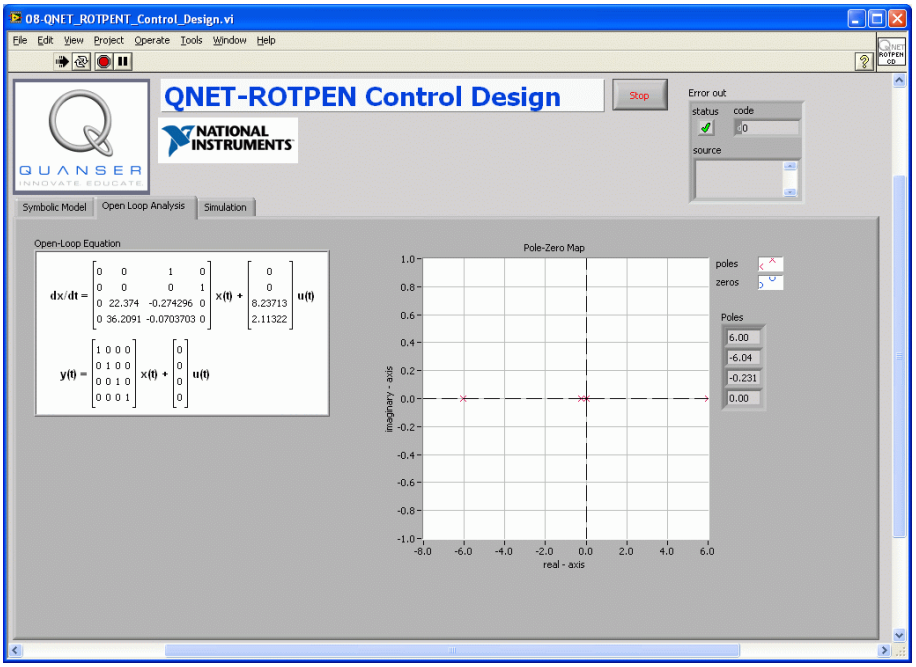


Figure 3.2: LabVIEW VI used to analyze open loop stability of QNET rotary pendulum system.

3.2.3 Simulation Tab

On the *Simulation* tab shown in Figure 3.3, users can generate the balance control gains for the QNET rotary pendulum system using LQR and simulate the closed-loop system.

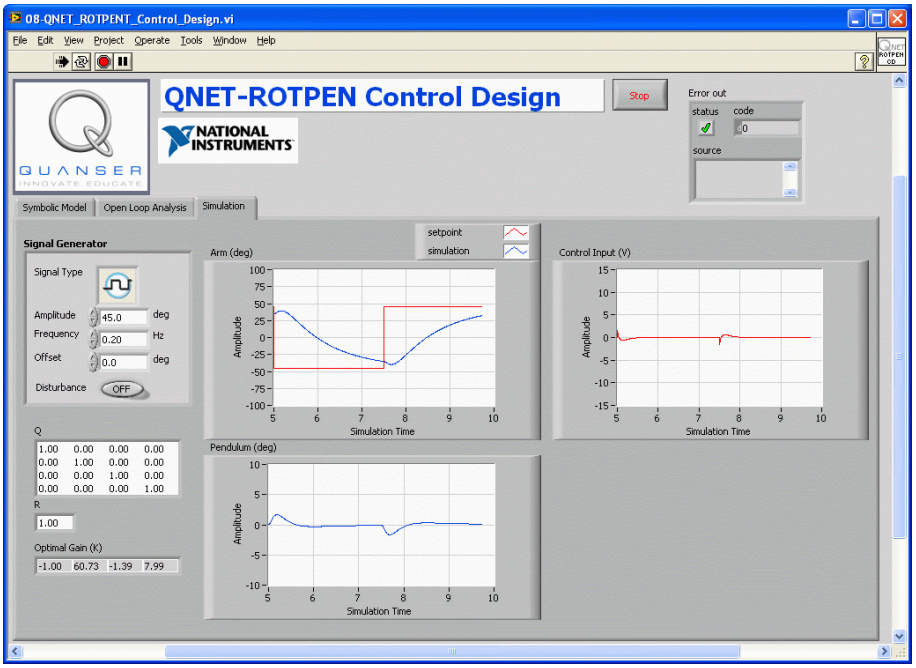


Figure 3.3: LabVIEW VI for QNET rotary pendulum balance control design.

3.3 Model Analysis [20 min]

1. Open the QNET_ROTPENT_Control_Design.vi.
2. Run the QNET_ROTPENT_Control_Design.vi. The front panel of the VI shown in Figure 3.1.
3. Select the *Symbolic Model* tab.
4. The *Model Parameters* array includes all the rotary pendulum modeling variables that are used in the state-space matrices A, B, C, and D.
5. Select the *Open Loop Analysis* tab, shown in Figure 3.2.
6. B-5, B-7 This shows the numerical linear state-space model and a pole-zero plot of the open-loop inverted pendulum system. What do you notice about the location of the open-loop poles? How does that affect the system?
   Recommended: In the *Model Parameters* section, it is recommended to enter the pendulum moment of inertia, *Jp*, be determined experimentally in Section 2.5.

   Answer 3.1

Outcome	Solution
B-5	If the VI was ran correctly, they should be able to draw some conclusions based on the pole locations.
B-7	The inverted rotary pendulum system is unstable because there is one pole in the right-hand plane.

   □□□
7. In the *Symbolic Model* tab, set the pendulum moment of inertia, *Jp*, to 1.0×10^{-5} kg $\cdot$ m^2.

8. K-1, B-9 Select the *Open Loop Analysis* tab. How did the locations of the open-loop poles change with the new inertia? Enter the pole locations of each system with a different moment of inertia. Are the changes of having a pendulum with a lower inertia as expected?

Answer 3.2

Outcome	Solution
K-1	The poles are at $\{9.0,-9.2,-0.35,0\}$ for $J_p = 1.7 \times 10^{-4}$ kg · m^2 and $\{11,-11.3,-0.35,0\}$ for $J_p = 1.0 \times 10^{-5}$ kg · m^2.
B-9	The poles in the right-hand plane (RHP) move further into the RHP when the inertia is decreased. This implies that it's is easier to stabilize or balance an inverted pendulum that has a larger moment of inertia. Which makes sense from a practical standpoint, e.g., it's easier to balance a broom stick with one hand then it is a pencil.

□□□

9. Reset the pendulum moment of inertia, *Jp*, back to 1.77×10^{-4} kg · m^2.
10. Stop the VI by clicking on the *Stop* button.

3.4 Control Design and Simulation [45 min]

1. Open the QNET_ROTPENT_Control_Design.vi.
2. Select the *Simulation* tab.
3. Run the VI. The VI running is shown Figure 3.3.
4. In the *Signal Generator* section set:
   - Amplitude = 45.0 deg
   - Frequency = 0.20 Hz
   - Offset = 0.0 deg
5. Set the *Q* and *R* LQR weighting matrices to the following:
   - Q(1,1) = 10, i.e., set first element of Q matrix to 10
   - R = 1

   Changing the *Q* matrix generates a new control gain.
6. B-5, K-1 The arm reference (in red) and simulated arm response (in blue) are shown in the *Arm (deg)* scope. How did the arm response change? How did the pendulum response change in the *Pendulum (deg)* scope.

Answer 3.3

Outcome	Solution
B-5	If the VI was ran correctly, they should be able to make the following observations.
K-1	The arm response becomes faster, i.e., peak time decreases, mainly due to the increased arm proportional gain. In the pendulum tends to deflect form its vertical position more as the gain is increased, however.

□□□

7. Set the third element in the *Q* matrix to 0, i.e., Q(3,3) = 0.
8. B-7 Examine and describe the change in the *Arm (deg)* and *Pendulum (deg)* scope.

Answer 3.4

Outcome	Solution
B-7	Decreasing this LQR term makes the arm response faster but the pendulum angle tends to overshoot more. The proportional and derivative gains of the pendulum go down when Q(3,3) decreases.

□□□

9. K-3 By varying the diagonal elements of the *Q* matrix, design a balance controller that adheres to the following specifications:

   - Arm peak time less than 0.75 s: $t_p \leq 0.75$ s.
   - Motor voltage peak less than $\pm$ 12.5 V: $|V_m| \leq 12.5$ V.
   - Pendulum angle less than 10.0 deg: $|\alpha| \leq 10.0$ deg.

   Record the *Q* and *R* matrices along with the control gain used to meet the specifications in your report.

Answer 3.5

Outcome	Solution
K-3	Using the weighting matrices

$$Q = \begin{bmatrix} 40 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

and $R = 1$, the following gain was generated

$$K = \begin{bmatrix} -6.32 & 81.2 & -2.76 & 10.87 \end{bmatrix} \qquad \text{(Ans.3.1)}$$

□□□

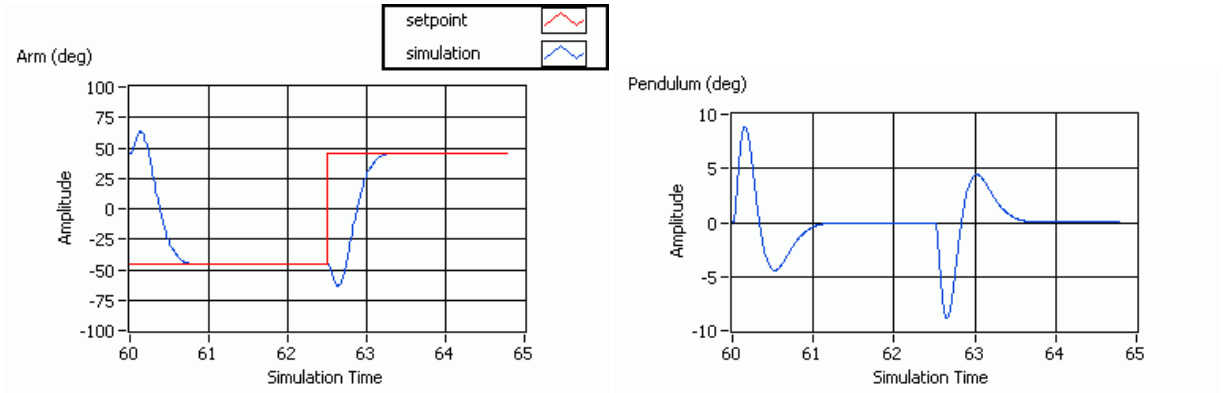
10. K-2, B-9 Attach the responses from the *Arm (deg)*, *Pendulum (deg)*, and *Control Input (V)* scopes when using your designed balance controller. Does it satisfy the specifications?

Answer 3.6

Outcome	Solution
K-2	The simulated closed-loop response of the QNET rotary inverted pendulum is given in Figure 3.4. This is using the LQR gain given in Equation Ans.3.1.
B-9	The response in Figure 3.4 meets the specifications given in Step 9.

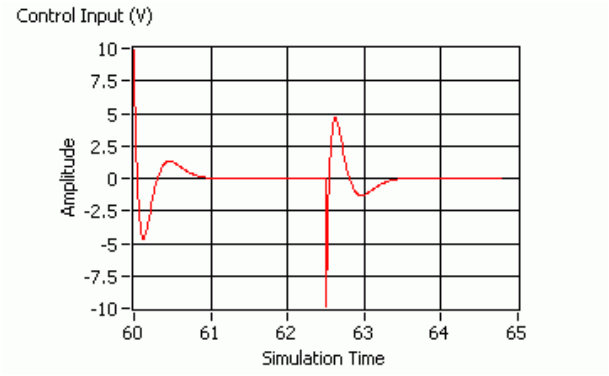
□□□

11. Stop the VI by clicking on the *Stop* button.



(a) Rotary Arm

(b) Pendulum Link



(c) Motor Voltage

Figure 3.4: Simulated rotary inverted pendulum response.

4 BALANCE CONTROL IMPLEMENTATION

4.1 Background

Balancing is a common control task. In this experiment we will find control strategies that balance the pendulum in the upright position while maintaining a desired position of the arm. When balancing the system the pendulum angle, α, is small and balancing can be accomplished simply with a PD controller. If we are also interested in keeping the arm in a fixed position a feedback from the arm position will also be introduced. The control law can then be expressed as

$$u = -k_{p,\theta}(\theta - \theta_r) - k_{p,\alpha}(\alpha - \pi) - k_{d,\theta}\dot{\theta} - k_{d,\alpha}\dot{\alpha} \tag{4.1}$$

where $k_{p,\theta}$ is the arm angle proportional gain, $k_{p,\alpha}$ is the pendulum angle proportional gain, $k_{d,\theta}$ is the arm angle derivative gain, and $k_{d,\alpha}$ is the pendulum angle derivative gain. The desired angle of the arm is denoted by θ_r and there is no reference for the pendulum angle because the desired position is zero.

There are many different ways to find the controller parameters. As discussed in Section 3.1, one method is based on LQR-optimal control. Initially, however, the behaviour of the system will be explored using default parameters.

When balancing the pendulum over a fixed point, the arm tends to oscillate about that reference because of the friction present in the motor. Due to friction, the motor will not move until the control signal is sufficiently large and the generated torque is larger than the stiction (see Section 2.1 for more details). This means that the pendulum has to fall a certain angle before the motor moves and the net result is an oscillating motion.

Friction can be compensated by introducing a Dither signal at the input voltage of the DC motor. The Dither signal used has the form

$$V_d = A_d \sin f_d t + V_{d0}$$

where A_d is the voltage amplitude, f_d is the sinusoid frequency, and V_{d0} is the offset voltage of the signal.

See Wikipedia for more information on PID and friction.

4.2 Balance Control VI

The virtual instrument used to run the balance controller (and the swing-up, shown later) on the QNET rotary pendulum system is shown in Figure 4.1.

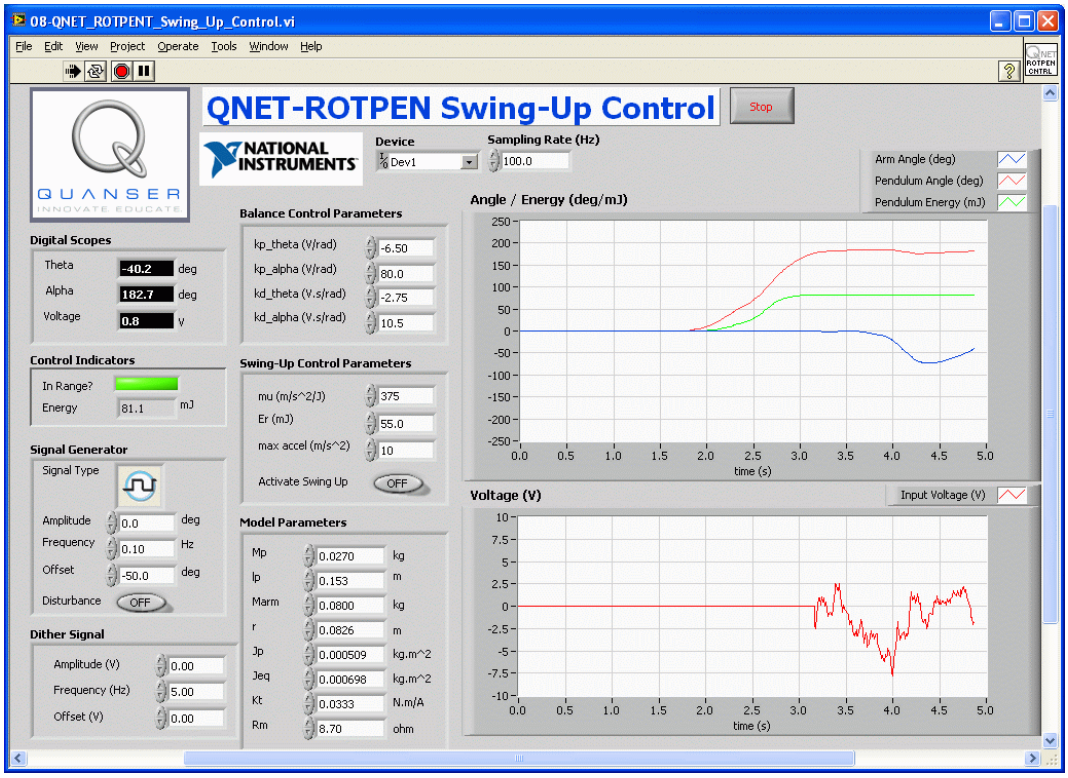


Figure 4.1: LabVIEW VI for QNET rotary pendulum balancing control (and swing-up).

4.3 Default Balance Control [30 min]

1. Open the QNET_ROTPENT_Swing_Up_Control.vi and ensure it is configured as described in Section 6. **Make sure the correct *Device* is chosen.**
2. Run the QNET_ROTPENT_Swing_Up_Control.vi. The VI should appear similarity as shown in Figure 4.1.
3. In the *Signal Generator* section set:
   - Amplitude = 0.0 deg
   - Frequency = 0.10 Hz
   - Offset = 0.0 deg
4. In the *Balance Control Parameters* section set:
   - kp_theta = -6.5 V/rad
   - kp_alpha = 80 V/rad
   - kd_theta = -2.75 V/(rad/s)
   - kd_alpha = 10.5 V/(rad/s)
5. In the *Swing-Up Control Parameters* section set:
   - mu = 55 m/s2/J
   - Er = 20.0 mJ
   - max accel = 10 m/s2
   - Activate Swing-Up = OFF (de-pressed)
6. Adjust the *Angle/Energy (deg/mJ)* scope scales to see between -250 and 250 (see Reference [2] for help).

7. Manually rotate the pendulum in the upright position until the *In Range?* LED in the *Control Indicators* section turns bright green. **Ensure the encoder cable does not interfere with the pendulum arm motion.**

8. B-5, K-1 Vary Offset and observe the *Arm Angle (deg)* response in the *Angle/Energy (deg/mJ)* scope. **Do not set the *Offset* too high or the encoder cable will interfere with the pendulum arm motion.**

Answer 4.1

Outcome	Solution
B-5	If the VI was ran correctly and the pendulum is being balance, then they should be able to make some observations below.
K-1	The *Offset* input box in the *Signal Generator* generates a constant set-point. The rotary arm is stabilized about the set offset angle.

□□□

9. K-1 As the pendulum is being balanced, describe the red *Arm Angle (deg)* and the blue *Pendulum Angle (deg)* responses in the *Angle/Energy (deg/mJ)* scope.

Answer 4.2

Outcome	Solution
K-1	Both are stabilized but students may notice that the rotary arm tends to rotate back-and-forth about the set offset angle.

□□□

10. In the *Signal Generator* section set:

- Amplitude = 45.0 deg
- Frequency = 0.10 Hz
- Offset = 0.0 deg

11. B-7 Observe the behaviour of the system when a square wave command is given to the arm angle. Why does the arm initially move in the wrong direction?

Answer 4.3

Outcome	Solution
B-7	This is necessary to keep the pendulum balanced. If the arm didn't go back a bit before moving forward then the pendulum would have a tendency to rotates downwards and go unstable. The technical answer is the system is non-minimum phase.

□□□

12. Click on the *Stop* button to stop running the VI.

4.4 Implement Designed Balance Control [20 min]

1. Go through Section 3.4 and design a balance control according to the given specifications.
Remark: It is recommended to use the experimental determined pendulum moment of inertia that was found in Section 2.5.

2. Open the QNET_ROTPENT_Swing_Up_Control.vi and ensure it is configured as described in Section 6. **Make sure the correct *Device* is chosen.**

3. Run the QNET_ROTPENT_Swing_Up_Control.vi. The VI should appear similarity as shown in Figure 4.1.

4. In the *Signal Generator* section set:

- Amplitude = 45.0 deg

- Frequency = 0.20 Hz
- Offset = 0.0 deg

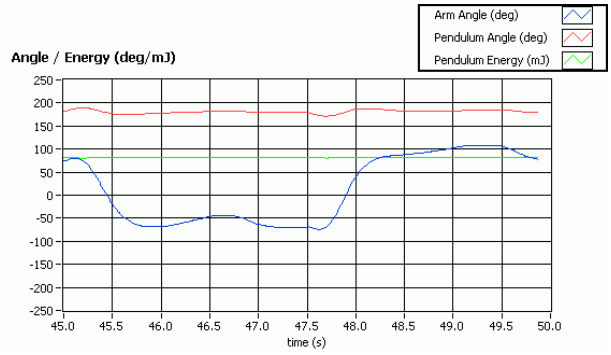
5. To implement your balance controller, enter the control gain found in Section 3.4 in *kp_theta*, *kp_alpha*, *kd_theta*, and *kd_alpha* in the *Control Parameters* section.

6. Manually rotate the pendulum in the upright position until the *In Range?* LED in the *Control Indicators* section turns bright green. **Ensure the encoder cable does not interfere with the pendulum arm motion.**

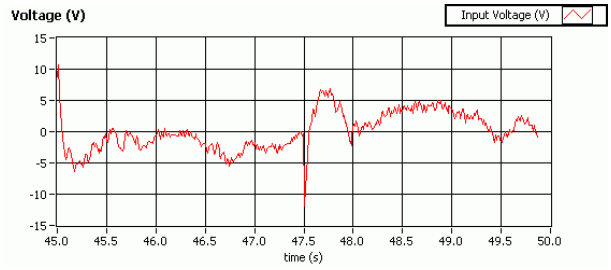
7. B-5, K-2, B-9 Attach the response found *Angle/Energy (deg/mJ)* and the *Voltage (V)* scopes. Does your system meet the specifications given in Section 3.4?

Answer 4.4

Outcome	Solution
B-5	If the student was able to get the response given in Figure 4.2, then the procedure to run the VI was done properly.
K-2	The measured closed-loop response of the QNET rotary inverted pendulum is given in Figure 4.2. This is using the LQR gain given in Equation Ans.3.1.
B-9	As shown in Figure 4.2, the arm peak time is around 0.75 seconds, the input motor voltage is within $\pm$ 10.5 V, and the pendulum oscillates $\pm$ 5 deg about the vertical position. So the specifications given in Section 3.4 are satisfied.



(a) Rotary Arm, Pendulum Angle, and Energy



(b) Motor Voltage

Figure 4.2: Simulated rotary inverted pendulum response.

□□□

8. Click on the *Stop* button to stop running the VI.

4.5 Balance Control with Friction Compensation [30 min]

1. Go through steps 1-7 in Section 4.3 to run the default balance control. The pendulum should be balancing.

2. In the *Signal Generator* section set:
   - Amplitude = 0.0 deg
   - Frequency = 0.10 Hz
   - Offset = 0.0 deg
3. In the *Dither Signal* section set:
   - Amplitude = 0.00 V
   - Frequency = 2.50 Hz
   - Offset = 0.00 V
4. B-5, B-8 Observe the behaviour of *Arm Angle (deg)* in the *Angle/Energy (deg/mJ)* scope. Intuitively speaking, can you find some reasons why the arm is oscillating?

Answer 4.5

Outcome	Solution
B-5	If the procedure was followed correctly and pendulum is balancing, they should be able to make the following analysis.
B-8	Due to static friction found in motor, it typically takes at least $\pm$ 2.5 V to get the rotor moving. As a result, the pendulum has to fall enough such that the balance controller generates over $\pm$ 2.5 V. To keep the pendulum balanced, the arm has to move back-and-forth and this is why is oscillates about the offset angle.

□□□

5. Increase the *Amplitude* in the *Dither Signal* section by steps of 0.1 V until you notice a change in the arm angle response.
6. K-1 From the *Voltage (V)* scope and the pendulum motion, what is the Dither signal doing? Compare the response of the arm with and without the Dither signal.

Answer 4.6

Outcome	Solution
K-1	The Dither signal applied a sinusoidal voltage signal to the motor. This is added to the balance control signal. Adding the Dither reduces the amount of arm oscillation. For example, without the Dither the arm would oscillate between -25 and 40 degrees. When adding a Dither with 3.50 V at 2.50 Hz the arm would oscillate between -5 and -13 degrees.

□□□

7. Increase the *Frequency* in the *Dither Signal* section starting from 1.00 to 10.0 Hz.
8. B-7 How does this effect the pendulum arm response?

Answer 4.7

Outcome	Solution
B-7	In general, increasing the frequency minimizes the amount the arm oscillation about a certain angle. For example, the arm will tend to move back-and-forth more with a Dither of 3.0 V at 1.0 Hz then with a Dither of 3.0 V at 2.5 Hz. However, increasing the Dither frequency too much causes the pendulum arm to vibrate without improving the swing that much.

□□□

9. B-9 Set the *Dither Signal* properties according to the friction measured in Section 2.4. How does this effect the pendulum arm response?

Answer 4.8

Outcome	Solution
B-9	By using the identified Coulomb friction, the oscillatory arm angle response should be minimized optimally.

□□□

10. Click on the *Stop* button to stop running the VI.

5 SWING-UP CONTROL

5.1 Background

5.1.1 Energy Control

If the arm angle is kept constant and the pendulum is given an initial position it would swing with constant amplitude. Because of friction there will be damping in the oscillation. The purpose of energy control is to control the pendulum in such a way that the friction is constant. The potential energy of the pendulum is

$$E_p = M_p\, g\, l_p\, (1 - \cos\alpha) \tag{5.1}$$

and the kinetic energy is

$$E_k = \frac{1}{2} J_p \dot{\alpha}^2. \tag{5.2}$$

The potential energy is zero when the pendulum is at rest at $\alpha = 0$ in Figure 2.2, and equals $2M_p\, g\, l_p$ when the pendulum is upright at $\alpha = \pm\pi$. The sum of the potential and kinetic energy of the pendulum is

$$E = \frac{1}{2} J_p \dot{\alpha}^2 + M_p\, g\, l_p\, (1 - \cos\alpha)\,. \tag{5.3}$$

Differentiating 5.3 results in the differential equation

$$\dot{E} = \dot{\alpha}\left(J_p \ddot{\alpha}^2 + M_p\, g\, l_p \sin\alpha\right). \tag{5.4}$$

Substituting the pendulum equation of motion given in Equation 2.1 for pendulum acceleration into Equation 5.4 gives

$$\dot{E} = M_p\, u\, l_p\, \dot{\alpha} \cos\alpha.$$

Since the acceleration of the pivot is proportional to current driving the arm motor and thus also proportional to the drive voltage we find that it is easy to control the energy of the pendulum. The proportional control law

$$u = (E_r - E)\, \dot{\alpha} \cos\alpha \tag{5.5}$$

drives the energy towards the reference energy E_r. Notice that the control law is nonlinear because the proportional gain depends on the pendulum angle, α. Also, notice that the control changes sign when $\dot{\alpha}$ changes sign and when the angle is $\pm$ 90 deg.

However, for energy to change quickly the magnitude of the control signal must be large. As a result the following swing-up controller is implemented in the LabVIEW VI

$$u = \text{sat}_{u_{max}}\left(\mu(E_r - E)\text{sign}(\dot{\alpha}\cos\alpha)\right) \tag{5.6}$$

where μ is a tunable control gain and the $\text{sat}_{u_{max}}$ function saturates the control signal at the maximum acceleration of the pendulum pivot, u_{max}.

See Wikipedia for more information on potential energy, kinetic energy, control theory, and nonlinear control.

5.1.2 Hybrid Swing-Up Control

The energy swing-up control in 5.5 (or 5.6 can be combined with the balancing control law in 4.1 to obtain a control law which performs the dual tasks of swinging up the pendulum and balancing it. As illustrated in Figure 5.1, this can be accomplished by switching between the two control systems.

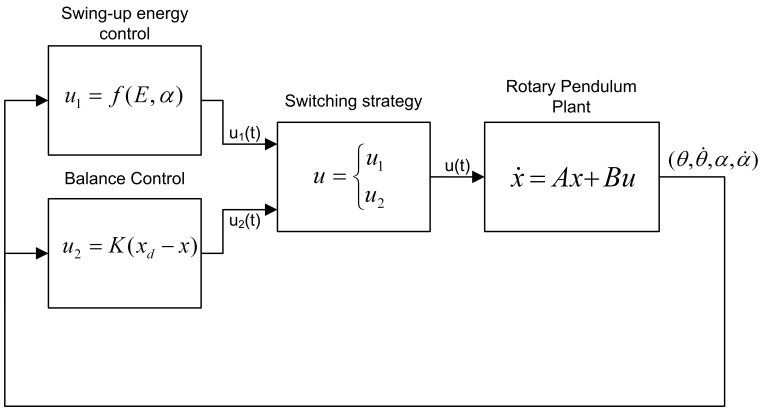


Figure 5.1: Swing-up hybrid control

This system can be modeled as a hybrid system. Hybrid systems are systems with both continuous and discrete parts. There are two continuous part: the closed-loop system using the swing-up energy controller and the closed-loop system using the PD balance controller. The switching strategy is the discrete element that chooses which controller, or system, to run. The switching logic can be obtained by determining a region in state space where the balancing works well. Balancing control is then used inside this region and energy control is used outside the region. Figure 5.2 is a called a hybrid automaton and, for this specific task, can be used to describe the system model and the switching logic.

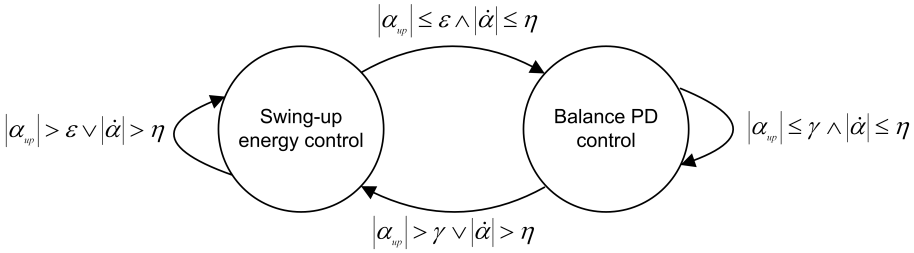

$|\alpha_{up}| \le \varepsilon \wedge |\dot{\alpha}| \le \eta$
$|\alpha_{up}| > \varepsilon \vee |\dot{\alpha}| > \eta$
Swing-up energy control
Balance PD control
$|\alpha_{up}| \le \gamma \wedge |\dot{\alpha}| \le \eta$
$|\alpha_{up}| > \gamma \vee |\dot{\alpha}| > \eta$

Figure 5.2: Hybrid swing-up controller automaton

The circles in Figure 5.2 are called *locations* and represent the two different continuous system. The arrows are called *edges* and represent the discrete jumps taken when certain condition are satisfied. The angle used in the switching logic in Figure 5.2 is called the upright angle. It is defined as zero when the pendulum is about its upright vertical position and expressed mathematically using

$$\alpha_{up} = \alpha \text{ mod } 2\pi - \pi.$$

The various switching parameters shown in Figure 5.2 can then be set as:

$$\begin{aligned} \epsilon &= 2 \text{ deg} \\ \eta &= 720 \text{ deg/s} \\ \gamma &= 30 \text{ deg} \end{aligned}$$

Given that the pendulum starts in the downward vertical position, it is in the swing-up location of the hybrid automaton. The swing-up controller pumps energy into the pendulum until it swings within $\pm$ 2 deg of its upright vertical position. Once the pendulum is within that that range and does not exceed 720 deg/s in either direction, the edge is taken to engage the balance controller. It remain in the *Balance PD control* location until the pendulum goes beyond the $\pm$ 30 deg position range or beyond $\pm$ 720 deg/s.

5.2 Swing-Up Control VI

The virtual instrument used to run the swing-up controller on the QNET rotary pendulum system is the same as the balance control given in Section 4.2 shown in Figure 4.1.

5.3 Energy Control [30 min]

1. Open the QNET_ROTPENT_Swing_Up_Control.vi and ensure it is configured as described in Section 6. **Make sure the correct *Device* is chosen.**
2. Run the QNET_ROTPENT_Swing_Up_Control.vi. The VI should appear similarity as shown in Figure 4.1.
3. In the *Balance Control Parameters* section ensure the following parameters are set:
   - kp_theta = -6.50 V/rad
   - kp_alpha = 80.0 V/rad
   - kd_theta = -2.75 V/(rad/s)
   - kd_alpha = 10.5 V/(rad/s)
4. In the *Swing-Up Control Parameters* section set:
   - mu = 55 m/s^2/J
   - Er = 20.0 mJ
   - max accel = 10 m/s^2
   - Activate Swing-Up = OFF (de-pressed)
5. Adjust the *Angle/Energy (deg/mJ)* scope scales to see between -250 and 250 (see the ROTPEN User Manual ([2]) for help).
6. Manually rotate the pendulum at different levels and examine the blue *Pendulum Angle (deg)* and the green *Pendulum Energy (mJ)* in the *Angle/Energy (deg/mJ)* scope. The pendulum energy is also displayed numerically in the *Control Indicators* section.
7. B-5, K-1 What do you notice about the energy when the pendulum is moved at different positions? Record the energy when the pendulum is being balanced (i.e., fully inverted in the upright vertical position).

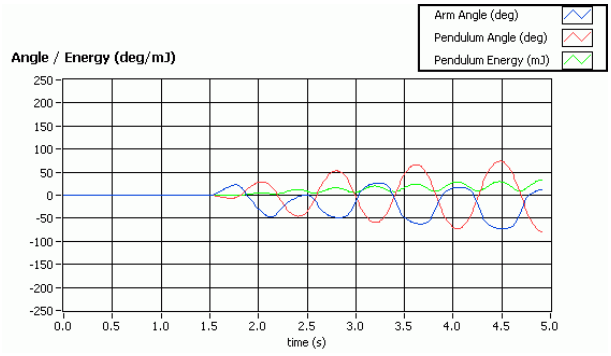
   Answer 5.1

Outcome	Solution
B-5	If they followed the procedure correctly, they should be able to perform the following analyssi as well as measure the energy.
K-1	The pendulum energy increases proportionally with the pendulum angle. When being balanced, the energy read is 81.0 mJ.

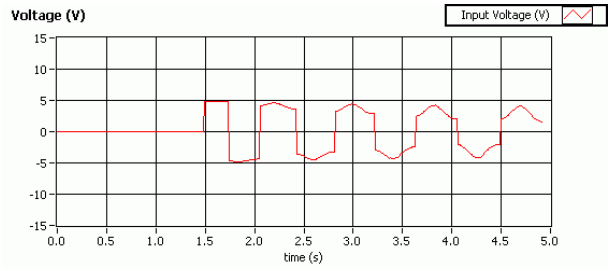
   □□□
8. Click on the *Stop* button to bring the pendulum down to the gantry position and re-start the VI.
9. In the *Swing-Up Control Parameters* section, turn ON the *Activate Swing-Up* switch (the pressed down position).
10. If the pendulum is not moving, click on the *Disturbance* button in the *Signal Generator* section to perturb the pendulum.
11. B-7, K-2 In *Swing-Up Control Parameters*, change the reference energy *Er* between 5.0 mJ and 50.0 mJ. As it is varied, examine the control signal in the *Voltage (V)* scope as well as the blue *Pendulum Angle (deg)* and the red *Pendulum Energy (mJ)* in the *Angle/Energy (deg/mJ)* scope. Attach the response of the *Angle/Energy (deg/mJ)* and *Voltage (V)* scopes.

Answer 5.2

Outcome	Solution
B-7	The larger the reference energy, the large the amplitude of the control signal.
K-2	The responses shown in Figure 5.3 are using energy control with *mu* = 55 m/s^2/J and *Er* = 50 mJ, and *max accel* = 10 m/s^2.



(a) Rotary Arm, Pendulum Angle, and Energy



(b) Motor Voltage

Figure 5.3: Pendulum response using energy control with $E_r = 50$ mJ.

□□□

12. B-7 In *Control Parameters* fix *Er* to 20.0 mJ and vary the swing-up control gain *mu* between 10 and 100 m/s^2/J. Describe how this changes the performance of the energy control.

Answer 5.3

Outcome	Solution
B-7	As the *mu* gain increases the amplitude of the pendulum swings become larger. Recall from swing-up controller given in 5.6, which is implemented in the VI, that μ is the proportional gain.

□□□

13. Click on the *Stop* button to stop running the VI.

5.4 Hybrid Swing-Up Control [20 min]

1. Open the QNET_ROTPENT_Swing_Up_Control.vi and ensure it is configured as described in Section 6. **Make sure the correct *Device* is chosen.**
2. Run the QNET_ROTPENT_Swing_Up_Control.vi. The VI should appear similarity as shown in Figure 4.1.
3. In the *Balance Control Parameters* section ensure the following parameters are set:
   - kp_theta = -6.50 V/rad

- kp_alpha = 80.0 V/rad
- kd_theta = -2.75 V/(rad/s)
- kd_alpha = 10.5 V/(rad/s)

4. In the *Swing-Up Control Parameters* section set:
   - mu = 55 m/s^2/J
   - Er = 20.0 mJ
   - max accel = 10 m/s^2
   - Activate Swing-Up = OFF (de-pressed)
5. Adjust the *Angle/Energy (deg/mJ)* scope scales to see between -250 and 250 (see the ROTPEN User Manual ([2] for help).
6. Make sure the pendulum is hanging down motionless and the encoder cable is not interfering with the pendulum.
7. In the *Swing-Up Control Parameters*, set the *Activate Swing-Up* switch to ON (pressed down position).
8. The pendulum should begin going back and forth. If not, click on the *Disturbance* button in the *Signal Generator* section to perturb the pendulum. **Turn off the *Active Swing-Up* switch if the pendulum goes unstable or if the encoder cable interferes with the pendulum arm motion.**
9. B-5 Gradually increase the reference energy *Er* in the *Control Parameters* section until the pendulum swings up to the vertical position.

Answer 5.4

Outcome	Solution
B-5	Setting the reference energy, E_r, between 80 and 85 mJ should be adequate to swing-up the pendulum to its vertical position.

□□□

10. B-9 What reference energy was required to swing-up the pendulum? Was this value expected?

Answer 5.5

Outcome	Solution
B-9	Between 80 and 85 mJ. This is inline with the potential energy of the pendulum that was measured in Step 7 in Section 5.3 when the pendulum is vertically upwards.

□□□

11. Click on the *Stop* button to stop running the VI.

6 SYSTEM REQUIREMENTS

Required Hardware

- NI ELVIS II (or NI ELVIS I)
- Quanser QNET Rotary Inverted Pendulum Trainer (ROTPENT). See QNET ROTPENT User Manual ([2]).

Required Software

- NI LabVIEW®2010 or later
- NI LabVIEW®Control Design and Simulation Module
- *ELVIS II Users*: NI ELVISmx (installs required NI DAQmx drivers)
- *ELVIS I Users*:
  - NI DAQmx
  - ELVIS CD 3.0.1 or later installed

■ **Caution: If these are not all installed then the VI will not be able to run!** Please make sure all the software and hardware components are installed. If an issue arises, then see the troubleshooting section in the QNET ROTPENT User Manual ([2]).

6.1 Overview of Files

File Name	Description
QNET ROTPENT User Manual.pdf	This manual describes the hardware of the QNET Rotary Pendulum Trainer system and how to setup the system on the ELVIS.
QNET ROTPENT Workbook (Student).pdf	This laboratory guide contains pre-lab questions and lab experiments demonstrating how to design and implement controllers on the QNET DCMCT system LabVIEW®.
QNET_ROTPENT_Simple_Modeling.vi	Apply voltage to DC motor and examine the arm and pendulum responses.
QNET_ROTPENT_Control_Design.vi	Design and simulate LQR-based balance controller.
QNET_ROTPENT_Swing_Up_Control.vi	Swing-up and balance pendulum.
QNET DCMCT Workbook (Instructor).pdf	Same as the student version except it includes the exercise solutions.

Table 2: Instructor design files supplied with the QNET ROTPENT Laboratory.

6.2 Simple Modeling Laboratory VI

The QNET-ROTPENT Simple Modeling VI is shown in Figure 6.1. It runs the DC motor connected to the pendulum arm in open-loop and plots the corresponding pendulum arm and link angles as well as the applied input motor voltage. Table 3 lists and describes the main elements of the ROTPENT Simple Modeling virtual instrument front panel. Every element is uniquely identified through an ID number and located in Figure 6.1.

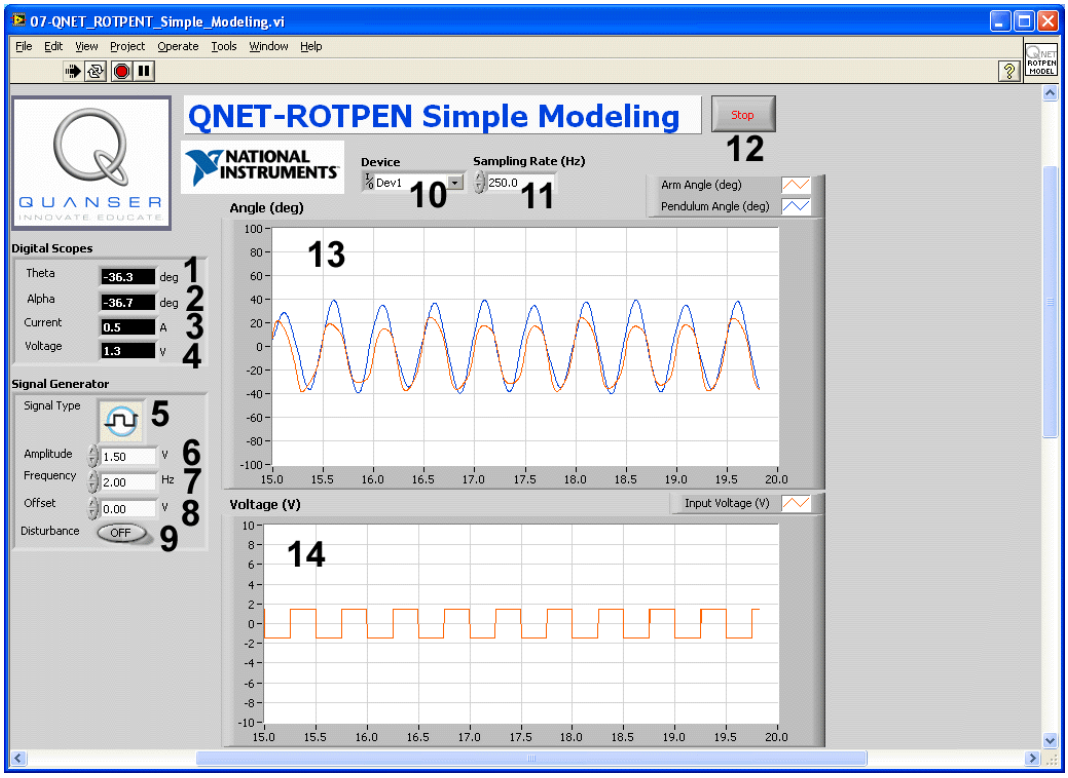


Figure 6.1: QNET-ROTPENT Simple Modeling virtual instrument.

6.3 Control Design VI

The QNET ROTPENT Control Design VI enables users to design a balance controller and simulate its response. The matrices for the state-space model of the rotary inverted pendulum system is shown in the *Symbolic Model* tab and illustrated in Figure 6.2. The values of the variables used in the state-space model can be changed. In the *Open Loop Analysis* tab, shown in Figure 6.3, the numerical state-space model is displayed and the resulting open-loop poles are plotted on a phase plane. Based on this model, a controller to balance the rotary inverted pendulum system can be designed using the Linear-Quadratic Regulator (LQR) optimization technique, as shown in the *Simulation* tab in Figure 6.4. The resulting closed-loop inverted pendulum system can be simulated. Table 4 lists and describes the main elements of the ROTPENT Control Design virtual instrument user interface. Every element is uniquely identified through an ID number and located in figures 6.2, 6.3, and 6.4.

6.4 Swing-Up Control VI

The QNET Rotary Pendulum Trainer Swing-Up Control VI implements an energy-based control that swings up the pendulum to its upright vertical position and a state-feedback controller to balance the pendulum when in its upright position. The main elements of the VI front panel are summarized in Table 5 and identified in Figure 6.5 through the corresponding ID number.

ID #	Label	Symbol	Description	Unit
1	Theta	θ	Arm angle numeric display measured by encoder on motor.	deg
2	Alpha	α	Pendulum angle numeric display measured by encoder on pendulum pivot.	deg
3	Current	I_m	Motor armature current numeric display.	A
4	Voltage	V_m	Motor input voltage numeric display.	V
5	Signal Type		Type of signal generated for the input voltage signal.	
6	Amplitude		Generated signal amplitude input box.	V
7	Frequency		Generated signal frequency input box.	Hz
8	Offset		Generated signal offset input box.	V
9	Disturbance	V_{sd}	Apply simulated disturbance voltage.	V
10	Device		Selects the NI DAQ device.	
11	Sampling Rate		Sets the sampling rate of the VI.	Hz
12	Stop		Stops the LabVIEW VI from running.	
13	Scopes: Angle	θ, α	Scope with measured arm angle (in red) and pendulum angle (in blue).	deg
14	Scopes: Voltage	V_m	Scope with applied motor voltage (in red).	V

Table 3: QNET ROTPENT Simple Modeling VI Components

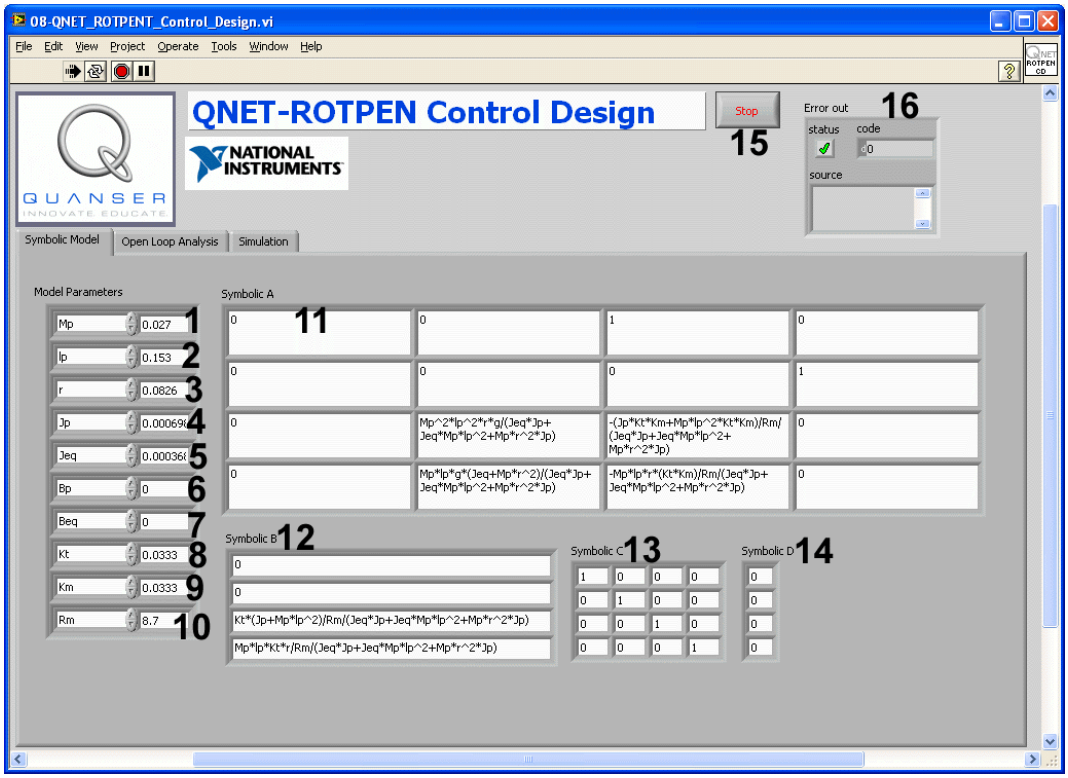


Figure 6.2: QNET ROTPENT Control Design VI: *Symbolic Model* tab.

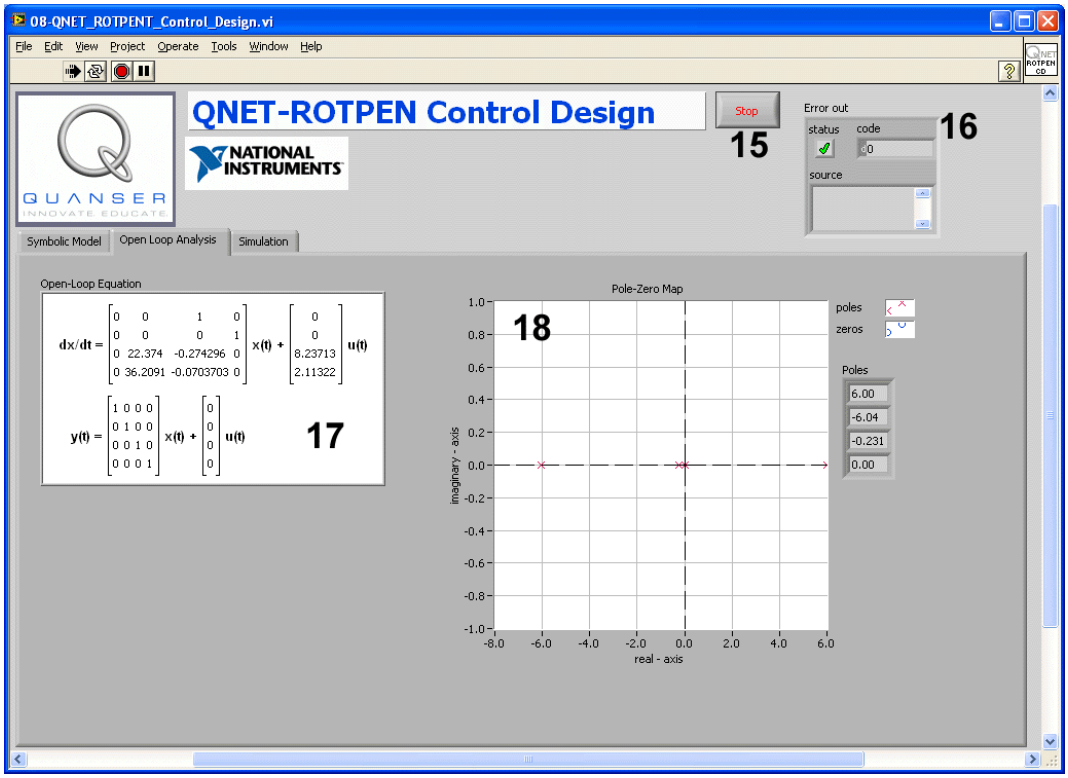


Figure 6.3: QNET ROTPENT Control Design VI: *Open Loop Analysis* tab.

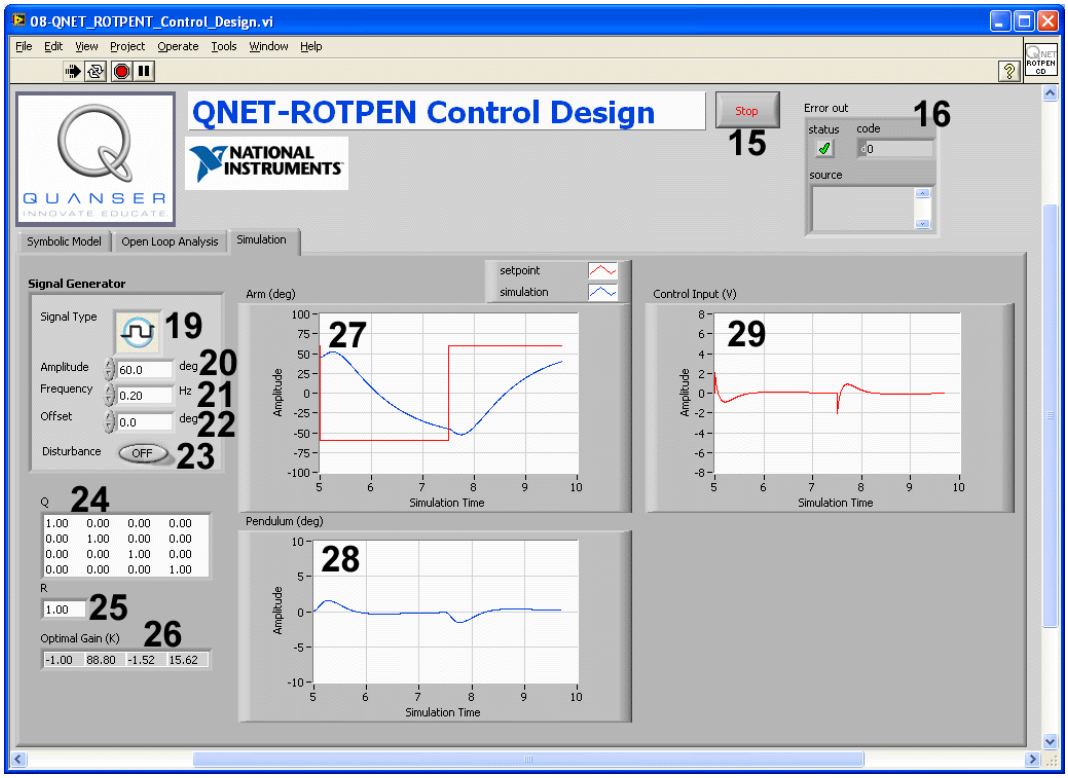


Figure 6.4: QNET ROTPENT Control Design VI: *Simulation*tab.

ID #	Label	Symbol	Description	Unit
1	Mp	M_p	Mass of pendulum assembly (link + weight).	kg
2	lp	l_p	Center of mass of pendulum assembly (link+weight) input box.	m
3	r	r	Length from motor shaft to pendulum pivot.	m
4	Jp	J_p	Pendulum moment of inertia relative to pivot.	kg.m2
5	Jeq	J_{eq}	Equivalent moment of inertia acting on the DC motor shaft.	kg.m2
6	Bp	B_p	Viscous damping about the pendulum pivot.	N.m.s/rad
7	Beq	B_{eq}	Equivalent viscous damping acting on the DC motor shaft.	N.m.s/rad
8	Kt	K_t	DC motor current-torque constant.	N.m/A
9	Km	K_m	DC motor back-emf constant.	V.s/rad
10	Rm	R_m	Electrical resistance of the DC motor armature.	Ω
11	Symbolic A	A	Rotary pendulum linear state-space matrix A.	
12	Symbolic B	B	Rotary pendulum linear state-space matrix B.	
13	Symbolic C	C	Rotary pendulum linear state-space matrix C.	
14	Symbolic D	D	Rotary pendulum linear state-space matrix D.	
15	Stop		Stops the LabVIEW VI from running.	
16	Error Out		Displays any error encountered in the VI.	
17	Open-Loop Equation		Numeric linear state-space model of rotary pendulum.	
18	Pole-Zero Map		Maps pole and zeros of open-loop rotary pendulum system.	
19	Signal Type		Type of signal generated for the arm position reference.	
20	Amplitude		Generated signal amplitude input box.	V
21	Frequency		Generated signal frequency input box.	Hz
22	Offset		Generated signal offset input box.	V
23	Disturbance	V_{sd}	Apply simulated disturbance voltage.	V
24	Q	Q	Linear-quadratic weighting matrix that defines a penalty on the state.	
25	R	R	Linear-quadratic weighting matrix that defines a penalty on the control action.	
26	Optimal Gain (K)	K	State-feedback control gain calculated using LQR.	
27	Arm	θ	Scope with reference (in blue) and measured (in red) arm angles.	deg
28	Pendulum	α	Scope with inverted pendulum angle (in blue).	deg
29	Control Input	V_m	Scope with applied motor voltage (in red).	V

Table 4: QNET ROTPENT Control Design VI Components

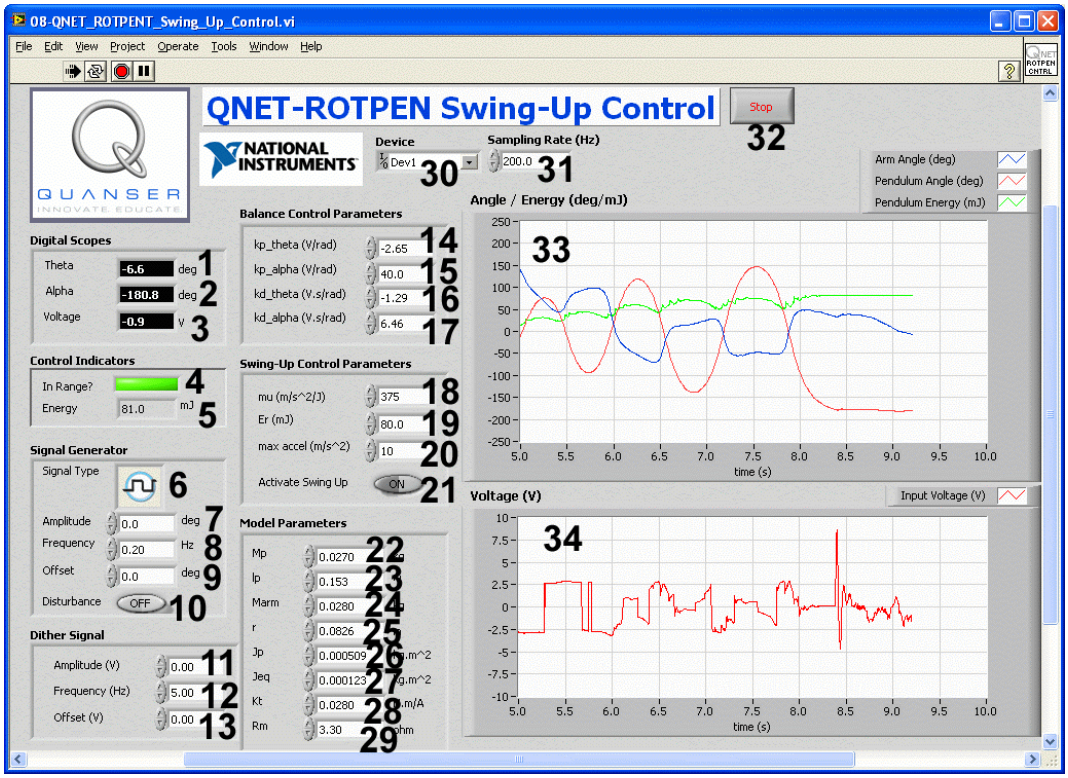


Figure 6.5: QNET ROTPENT Swing-Up Control VI.

ID #	Label	Symbol	Description	Unit
1	Theta	θ	Arm angle numeric display measured by encoder on motor.	deg
2	Alpha	α	Pendulum angle numeric display measured by encoder on pendulum pivot.	deg
3	Current	I_m	Motor armature current numeric display.	A
4	In Range?		Balance controller is engaged when this LED is turns bright green.	
5	Energy		Numeric display of the pendulum energy.	mJ
6	Signal Type		Type of signal generated for the arm reference signal (i.e., desired angle of arm).	
7	Amplitude		Reference position amplitude input box.	deg
8	Frequency		Reference position frequency input box.	Hz
9	Offset		Reference position offset input box.	deg
10	Disturbance	V_{sd}	Apply simulated disturbance voltage.	V
11	Amplitude	A_d	Dither signal amplitude input box.	V
12	Frequency	f_d	Dither signal frequency input box.	Hz
13	Offset	V_{d0}	Dither signal offset input box.	V
14	kp_theta	$k_{p,\theta}$	Arm angle proportional gain input box.	V/rad
15	kp_alpha	$k_{p,\alpha}$	Pendulum angle proportional gain input box.	V/rad
16	kd_theta	$k_{d,\theta}$	Arm angle derivative gain input box.	V.s/rad
17	kd_alpha	$k_{d,\alpha}$	Pendulum angle derivative gain input box.	V.s/rad
18	mu	μ	Proportional gain for energy controller.	m/(s2.J)
19	Er	E_r	Reference energy for energy controller.	mJ
20	Max accel	u_{max}	Maximum acceleration	m/s^2
21	Activate Swing Up		When pressed down the energy controller that swings-up the pendulum is engaged.	
22	Mp	M_p	Mass of pendulum assembly (link + weight).	kg
23	lp	l_p	Center of mass of pendulum assembly (link+weight) input box.	m
24	Marm	M_{arm}	Mass of rotary arm.	kg
25	r	r	Length from motor shaft to pendulum pivot.	m
26	Jp	J_p	Pendulum moment of inertia relative to pivot.	kg.m2
27	Jeq	J_{eq}	Equivalent moment of inertia acting on the DC motor shaft.	kg.m2
28	Kt	K_t	DC motor current-torque constant.	N.m/A
29	Rm	R_m	Electrical resistance of the DC motor armature.	Ω
30	Device		Selects the NI DAQ device.	
31	Sampling Rate		Sets the sampling rate of the VI.	Hz
32	Stop		Stops the LabVIEW VI from running.	
33	Scopes: Angle	θ, α	Scope with measured arm angle (in red) and pendulum angle (in blue).	deg
34	Scopes: Voltage	V_m	Scope with applied motor voltage (in red).	V

Table 5: QNET ROTPENT Swing-Up Control VI Components

7 LAB REPORT

This laboratory contains three groups of experiments, namely,

1. Modeling,
2. Balance control design
3. Balance control implementation
4. Swing-up control

For each experiment, follow the outline corresponding to that experiment to build the *content* of your report. Also, in Section 7.5 you can find some basic tips for the *format* of your report.

7.1 Template for Content (Simple Modeling)

I. PROCEDURE

1. *Damping*
   - Briefly describe the main goal of the experiment.
   - Briefly describe the experiment procedure in Step 6 in Section 2.3.
2. *Friction*
   - Briefly describe the main goal of the experiment.
   - Briefly describe the experiment procedure in Step 5 in Section 2.4.
3. *Moment of Inertia*
   - Briefly describe the main goal of the experiment.
   - Briefly describe the experiment procedure in Step 4 in Section 2.5.

II. RESULTS
Do not interpret or analyze the data in this section. Just provide the results.

1. Provide applicable data collected in this laboratory from Table 1.

III. ANALYSIS
Provide details of your calculations (methods used) for analysis for each of the following:

1. Damping analysis in step 6 in Section 2.3.
2. Finding friction in step 5 in Section 2.4.
3. Calculating moment of inertia of pendulum in step 4 in Section 2.5.

IV. CONCLUSIONS
Interpret your results to arrive at logical conclusions for the following:

1. How well does the experimentally derived moment of inertia compare with analytically derived value in step 5 of Section 2.5.

7.2 Template for Content (Balance Control Design)

I. PROCEDURE

1. *Model Analysis*
    - Briefly describe the main goal of the experiment.
    - Briefly describe the experimental procedure in Step 6 in Section 3.3.
2. *Control Design and Simulation*
    - Briefly describe the main goal of the experiment.
    - Briefly describe the experimental procedure in Step 6 in Section 3.4.

II. RESULTS

Do not interpret or analyze the data in this section. Just provide the results.

1. LQR matrices and control gain found in Step 9 in Section 3.4.
2. Simulated closed-loop response plot from Step 10 in Section 3.4.

III. ANALYSIS

Provide details of your calculations (methods used) for analysis for each of the following:

1. Open-loop poles in Step 6 in Section 3.3.
2. Effect of changing moment of inertia on open-loop poles in Step 8 in Section 3.3.
3. Effect of changing LQR elements on response in Step 6 in Section 3.4.
4. Effect of changing different LQR element on the response in Step 8 in Section 3.4.

IV. CONCLUSIONS

Interpret your results to arrive at logical conclusions for the following:

1. Does lowering the moment of inertia of the pendulum have the expected result Step 8 in Section 3.3.
2. Does the simulation match the specifications in Step 10 in Section 3.4.

7.3 Template for Content (Balance Control Implementation)

I. PROCEDURE

1. *Default Balance Control*
   - Briefly describe the main goal of the experiment.
   - Briefly describe the experimental procedure in Step 8 in Section 4.3.
2. *Implement Designed Balance Control*
   - Briefly describe the main goal of the experiment.
   - Briefly describe the experimental procedure in Step 7 in Section 4.4.
3. *Balance Control with Friction Compensation*
   - Briefly describe the main goal of this experiment.
   - Briefly describe the experimental procedure in Step 4 in Section 4.5.

II. RESULTS

Do not interpret or analyze the data in this section. Just provide the results.

1. Balance control response plot from step 7 in Section 4.4.

III. ANALYSIS

Provide details of your calculations (methods used) for analysis for each of the following:

1. Effect of changing offset in Step 8 in Section 4.3.
2. Balance control analysis in Step 9 in Section 4.3.
3. Balance control analysis when tracking step reference in 11 in Section 4.3.
4. Examining the arm oscillation in Step 4 in Section 4.5.
5. Explain what the Dither signal is doing in Step 6 in Section 4.5.
6. Effect of increasing Dither signal frequency in Step 8 in Section 4.5.

IV. CONCLUSIONS

Interpret your results to arrive at logical conclusions for the following:

1. Whether the balance controller meets the specifications in Step 7 in Section 4.4.
2. Effect of setting the Dither signal to the identified friction parameters in Step 9 of Section 4.5.

7.4 Template for Content (Swing-Up Control)

I. PROCEDURE

1. *Energy Control*
    - Briefly describe the main goal of the experiment.
    - Briefly describe the experimental procedure in Step 7 in Section 5.3.
2. *Hybrid Swing-Up Control*
    - Briefly describe the main goal of the experiment.
    - Briefly describe the experimental procedure in Step 9 in Section 5.4.

II. RESULTS

Do not interpret or analyze the data in this section. Just provide the results.

1. Pendulum response from Step 11 in Section 5.3.

III. ANALYSIS

Provide details of your calculations (methods used) for analysis for each of the following:

1. Energy at different pendulum position in Step 7 in Section 5.3.
2. Effect of changing reference energy in Step 11 in Section 5.3.
3. Effect of changing proportional gain in Step 11 in Section 5.3.

IV. CONCLUSIONS

Interpret your results to arrive at logical conclusions for the following:

1. Reference energy required to swing-up pendulum in Step 10 of Section 5.4.

7.5 Tips for Report Format

PROFESSIONAL APPEARANCE

- Has cover page with all necessary details (title, course, student name(s), etc.)
- Each of the required sections is completed (Procedure, Results, Analysis and Conclusions).
- Typed.
- All grammar/spelling correct.
- Report layout is neat.
- Does not exceed specified maximum page limit, if any.
- Pages are numbered.
- Equations are consecutively numbered.
- Figures are numbered, axes have labels, each figure has a descriptive caption.
- Tables are numbered, they include labels, each table has a descriptive caption.
- Data are presented in a useful format (graphs, numerical, table, charts, diagrams).
- No hand drawn sketches/diagrams.
- References are cited using correct format.

8 SCORING SHEETS

8.1 Simple Modeling: Pre-Lab Questions

Student Name :

Question[1]	A-1	A-2	A-3
1			
Total			

.

[1] This scoring sheet is for the Simple Modeling Pre-Lab questions in Section 2

8.2 Simple Modeling Lab Report

Student Name:

	CONTENT					FORMAT	
Item[1]	**K-1**	**B-5**	**B-6**	**B-7**	**B-9**	**GS-1**	**GS-2**
I. PROCEDURE							
I.1. Damping							
1							
I.2. Friction							
2							
I.3. Moment of Inertia							
3							
II. RESULTS							
1							
III. ANALYSIS							
1							
2							
3							
IV. CONCLUSIONS							
1							
Total							

[1] This scoring sheet corresponds to the report template in Section 7.1.

8.3 Balance Control Design: Lab Report

Student Name:

	CONTENT						FORMAT	
Item[1]	**K-1**	**K-2**	**K-3**	**B-5**	**B-7**	**B-9**	**GS-1**	**GS-2**
I. PROCEDURE								
I.1. Model Analysis								
1								
I.2. Control Design and Simulation								
2								
II. RESULTS								
1								
2								
III. ANALYSIS								
1								
2								
3								
4								
IV. CONCLUSIONS								
1								
2								
Total								

[1] This scoring sheet corresponds to the report template in Section 7.2.

8.4 Balance Control Implementation: Lab Report

Student Name:

	CONTENT						FORMAT	
Item[1]	**K-1**	**K-2**	**B-5**	**B-7**	**B-8**	**B-9**	**GS-1**	**GS-2**
I. PROCEDURE								
I.1. Default Balance Control								
1								
I.2. Implement Designed Balance Control								
2								
I.3. Balance Control with Friction Compensation								
3								
II. RESULTS								
1								
III. ANALYSIS								
1								
2								
3								
4								
5								
6								
IV. CONCLUSIONS								
1								
Total								

[1] This scoring sheet corresponds to the report template in Section 7.3.

8.5 Swing-Up Control: Lab Report

Student Name:

	CONTENT					FORMAT	
Item[1]	**K-1**	**K-2**	**B-5**	**B-7**	**B-9**	**GS-1**	**GS-2**
I. PROCEDURE							
I.1. Energy Control							
1							
I.2. Hybrid Swing-Up Control							
2							
II. RESULTS							
1							
III. ANALYSIS							
1							
2							
3							
IV. CONCLUSIONS							
1							
Total							

[1] This scoring sheet corresponds to the report template in Section 7.4.

Appendix A

QNET Instructor's Guide

Every laboratory in this manual is organized into four parts:

Background section provides all the necessary theoretical background for the experiments. Students should read this section first to prepare for the Pre-Lab questions and for the actual lab experiments.

Virtual Instrument introduces the LabVIEW® Virtual Instrument that is to be used for the lab experiment.

Lab Experiments section provides step-by-step instructions to conduct the lab experiments and to record the collected data. The lab may also include a set of pre-lab questions that need to be done prior to the lab experiments.

System Requirements section describes all the details of how to configure the hardware and software to conduct the experiments. It is assumed that the hardware and software configuration have been completed by the instructor or the teaching assistant *prior* to the lab sessions. However, if the instructor chooses to, the students can also configure the systems by following the instructions given in this section.

Assessment of ABET outcomes is incorporated into this manual as shown by indicators such as A-1, A-2 . These indicators correspond to specific performance criteria for an outcome.

A.1 Pre-lab Questions and Lab Experiments

A.1.1 How to use the pre-lab questions

All or some of the questions in the Pre-Lab Questions sections can be assigned to students as homework. One possibility is to assign them as a homework one week prior to the actual lab session and ask the students to bring their assignment to the lab session. This would help them get ready for the lab session. You should encourage them to study the background section of the chapter prior to attempting the pre-lab questions. **Note** that solutions for some of the Pre-Lab questions are parameters needed for the experiments in the lab session.

Another possibility is to go over some of these questions either in class or in the lab session together with the students. This could generate an interactive learning opportunity for them prior to the lab.

Finally, it is possible to use some of the pre-lab questions in your mid-term or final exams. This would reinforce the concepts covered in the labs; connections between the abstract theory and the real hardware; and would give you an option to integrate some of the work done in the lab sessions into your exams.

A.1.2 How to use the laboratory experiments

This manual is organized into several laboratory sections. Each section contains several experiments which are, for the most part, independent of each other. Therefore, one possible way to use this material is to conduct the individual experiments in your weekly lab sessions. Another possibility is to divide the class into teams and have each team conduct an experiment given in a section.

A.2 Assessment for ABET Accreditation

In the United States, accreditation is a peer-review process. Educational institutions or programs volunteer to undergo this review periodically to determine if certain criteria are being met. The *Accreditation Board for Engineering and Technology*, ABET, is responsible for the specialized accreditation of educational programs in applied science, computing, engineering, and technology. ABET accreditation is assurance that a college or university program meets the quality standards established by the profession for which it prepares its students.

It is the responsibility of the program seeking accreditation to demonstrate clearly that the program meets a set of criteria. One of these criteria is the ``Criterion 3: Program Outcomes". Engineering programs must demonstrate that their students attain program outcomes (a) through (k). Much more information about this can be found in the ``Criteria for Engineering Accreditation" document ABET publishes on its website annually (http://www.abet.org).

For fulfillment of Criterion 3, a program must show that there is an assessment and evaluation process in place that periodically documents and demonstrates the degree to which the program outcomes are attained by their students. Most programs do this by mapping the outcomes (a) through (k) to the courses in the curriculum[1]. Then, these outcomes are assessed in the courses. Finally, the assessment results are collected from the courses and compiled into program-level data to demonstrate the ``degree to which the program outcomes are attained by their students".

If your course is part of a similar assessment effort in your program, you probably need to assess the following outcomes in your course:

(A) An ability to apply knowledge of mathematics, science, and engineering,

(B) An ability to design and conduct experiments, as well as to analyze and interpret data,

(G) An ability to communicate effectively, and

(K) An ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

These outcomes can be assessed in your course using various assessment tools, such as student surveys and assignments or questions targeting specific outcomes. To measure achievement of an outcome (such as outcome ``A" in the list above), typically some performance criteria are defined for the outcome. The *performance criteria* are a set of measurable statements to define each learning outcome. They identify the specific knowledge, skills, attitudes, and/or behavior students must demonstrate as indicators of achieving the outcome.

For the purpose of this laboratory curriculum, we defined a set of performance criteria for each outcome. These criteria are labeled as ``A-1, A-2, B-3, ..., K-3" as indicated in the rubrics in Section A.3 below. We also embedded these performance criteria in the curriculum shown by indicators such as A-1, A-2 .

A.2.1 Assessment in your course

Assessment of outcomes is different than grading. A course grade (or a grade on an assignment or exam), is a composite indicator. For example, if a student receives "B" as a grade in your course, it is probably difficult to tell his/her level of achievement in outcome "A" versus "G". One of the purposes of assessment is to "measure" the level of achievement of these specific skills and knowledge so that improvements can be made in the future offerings of the course.

So, how should you introduce outcomes assessment into your course? The outcomes assessment approach described here can be applied to *each* pre-lab homework assignment and lab report of *each* student throughout the semester. This may or may not be feasible depending on your class size. In general, a *representative sample* of student work is assessed.

You can continue to give assignments/exams and grade them in the traditional way. To introduce assessment into your course, you can pick a representative sample of student work and "score" their work using the scoring sheets and rubrics given in this manual. This is a good way to start introducing assessment into your course.

[1] Disclaimer: The opionions expressed or the assessment techniques described here have not been endorsed by ABET in any way.

Recall that for fulfillment of Criterion 3, a program must ``document'' the assessment process. Programs collect sample student work in the academic year prior to the site visit by an ABET team. You can retain the sample homeworks, lab reports, their scoring sheets and the assessment workbook as ``evidence'' for the ongoing assessment effort in your course. This collection can then be given to the assessment committee in your program to be incorporated into the program-level evidence they will compile prior to the ABET site visit.

A.2.2 How to score the pre-lab questions

If you choose to assign the pre-lab questions as homework, then the outcome targetted by these questions can be assessed using the student work. The pre-lab questions require students to ``apply'' their math and engineering science knowledge through calculations and problem solving strategies. Therefore, outcome ``A'' was mapped to the pre-lab questions through its performance criteria.

If you assign the pre-lab questions as homework, you can ``score'' the returned homeworks using the rubric for outcome ``A'' given in Section A.3 and the scoring sheet provided for that pre-lab in that chapter.

To score homework of *one* student:

1. Print the scoring sheet for the Pre-Lab Questions section you assigned as homework. One sheet is used per student.
2. Use the rubric for ``Outcome A'' (Section A.3) to assign a score for each question. The rubric gives the description of ``levels of achievement'' (4 = exemplary, 3 = proficient, 2 = developing and 1 = beginning/incomplete) for each criterion. As an example, below is a completed sample scoring sheet after evaluating the homework of one student.

Question	A-1	A-2	A-3
1	3	2	
2	4	2	
3		3	
4		3	
5		4	
6		3	
7		3	
8		3	
9	3	3	
10		3	4
11		3	4
Total	10	32	8

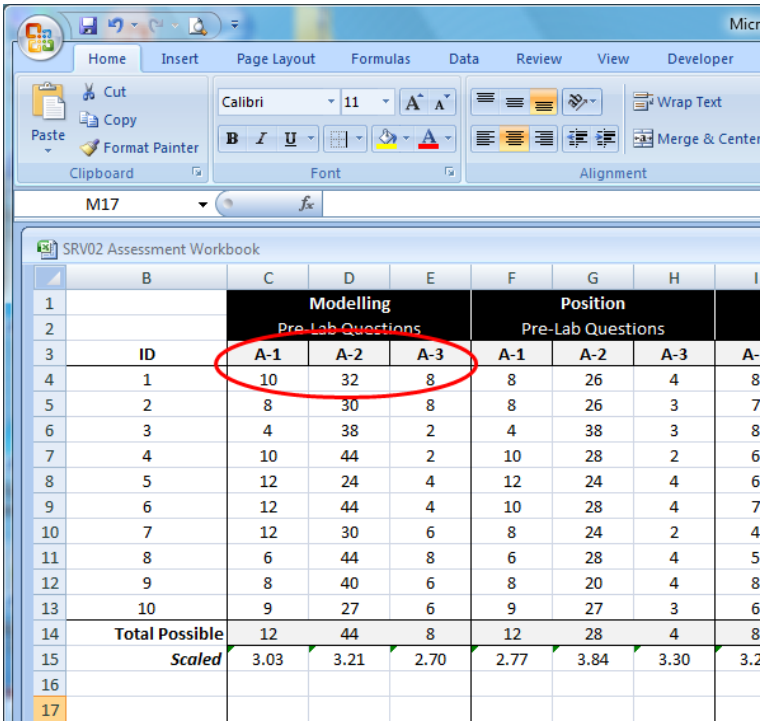
3. You can then enter the ``Total'' for each performance criterion into the assessment workbook [1] as shown in Figure A.1.

A.2.3 How to score the lab reports

As mentioned earlier in Section A.1.2, there are various ways in which you can use the material provided in this manual. In any case, the outcomes targetted by the lab experiments can be assessed from the lab reports submitted by the students. These reports should follow the specific template for content given at the end of each laboratory chapter. This will provide a basis to assess the outcomes easily.

The lab activities correspond to the ``applied'' part of engineering. Therefore, outcomes ``B'' and ``K'' were mapped to the lab activities through their performance criteria. The lab reports themselves match outcome ``G'' on effective communication skills.

If you choose to do an individual experiment in your weekly lab sessio then you can ask the students to submit a lab report using the report template provided for this experiment. The template contains the main ``content'' sections you



	B	C	D	E	F	G	H	I
1		Modelling			Position			
2		Pre-Lab Questions			Pre-Lab Questions			
3	ID	A-1	A-2	A-3	A-1	A-2	A-3	A-
4	1	10	32	8	8	26	4	8
5	2	8	30	8	8	26	3	7
6	3	4	38	2	4	38	3	8
7	4	10	44	2	10	28	2	6
8	5	12	24	4	12	24	4	6
9	6	12	44	4	10	28	4	7
10	7	12	30	6	8	24	2	4
11	8	6	44	8	6	28	4	5
12	9	8	40	6	8	20	4	8
13	10	9	27	6	9	27	3	6
14	Total Possible	12	44	8	12	28	4	8
15	*Scaled*	3.03	3.21	2.70	2.77	3.84	3.30	3.2
16								
17								

Figure A.1: Pre-Lab entry into the assessment workbook for one student.

would expect in a typical lab report (procedure, results, analysis, conclusions). Each section of the report template ties back to the activities in the lab and the corresponding assessment indicators. It also contains performance criteria related to the ``format'' of the report.

You can score the lab reports using the rubric for outcome ``G'' given in Section A.3 and the scoring sheet provided for the experiment in that section. **Note** that each lab report scoring sheet directly corresponds to the lab report content template for that experiment. Also, note that the rubric for outcome ``G'' already contains rubrics for outcomes ``B'' and ``K'' since these outcomes appear as an integral part of the report.

To score the lab report of *one* student:

1. Print the scoring sheet for the Lab Report for the experiment they conducted in the lab. One sheet is used per student.
2. Use the ``Content'' rubric (Section A.3) to assign a score for each entry in the scoring sheet. The rubric gives the description of ``levels of achievement'' (4 = exemplary, 3 = proficient, 2 = developing and 1 = beginning/incomplete) for each criterion. As an example, below is a completed scoring sheet after evaluating the lab report of one student.
3. Use the ``Format'' rubric (Section A.3) for the ``GS-1 and GS-2'' criteria to score the formatting of the report on the same scoring sheet.

	CONTENT						FORMAT	
Item[1]	**K-1**	**K-2**	**B-5**	**B-6**	**B-7**	**B-9**	**GS-1**	**GS-2**
I. PROCEDURE								
I.1. Frequency Response Experiment								
1			4					
I.2. Bump Test Experiment								
1			4					
I.3. Model Validation Experiment								
1			4					
II. RESULTS								
1		4						
2		3						
3		3						
4				3				
III. ANALYSIS								
III.1. Frequency Response Experiment								
1					2			
2	3							
III.2. Bump Test Experiment								
1	3							
IV. CONCLUSIONS								
1						3		
Total	6	10	12	3	2	3	4	3

4. You can then enter the ``Total" for each performance criterion into the assessment workbook [1] as show in Figure A.2.

	B	C	D	E	F	G	H	I	J	K
		Modelling								
		Lab Report Content						Report Format		
	ID	K-1	K-2	B-5	B-6	B-7	B-9	GS-1	GS-2	
	1	6	10	12	3	5	3	4	3	
	2	8	12	8	4	4	4	2	2	
	3	8	8	8	4	4	4	4	3	
	4	8	8	8	4	3	4	4	4	
	5	8	12	10	4	3	4	3	4	
	6	6	10	10	3	4	3	3	3	
	7	5	8	10	4	4	3	4	4	
	8	5	7	12	3	4	2	4	4	
	9	7	9	12	3	4	3	3	4	
	10	7	9	10	2	3	4	4	4	
	Total Possible	8	12	12	4	4	4	4	4	
	Scaled Average	3.40	3.10	3.33	3.40	3.80	3.40	3.50	3.50	
	Std. Dev.	1.23	1.70	1.63	0.70	0.63	0.70	0.71	0.71	

Figure A.2: Lab report score entries in the workbook for one student.

A.2.4 Assessment of the outcomes for the course

As explained earlier, the performance criteria, such as A-1, A-2, A-3, are used to describe a set of measurable statements to define each learning outcome. Up to this point, we explained how to assess each performance criterion using the pre-labs, the lab reports and the scoring sheets.

A *single* score for each outcome can be computed to indicate the level of attainment of that outcome by the entire class. One approach is to simply average the scores for the performance criteria for that outcome. For example, in case of outcome ``A", you can use:

$$SCORE_A = \frac{SCORE_{A-1} + SCORE_{A-2} + SCORE_{A-3}}{3} \tag{A.1}$$

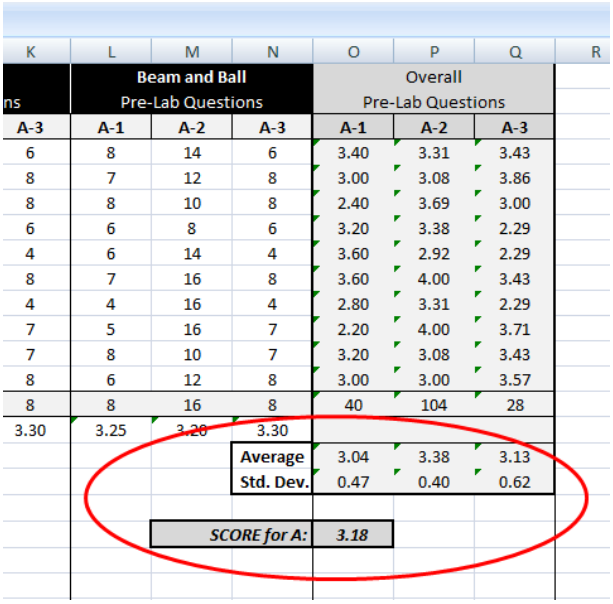
Another possibility is to use a weighted-average where some of the performance criteria are considered to be more important than the others. In case of outcome ``A", you can use:

$$SCORE_A = \frac{w_1 \cdot SCORE_{A-1} + w_2 \cdot SCORE_{A-2} + w_3 \cdot SCORE_{A-3}}{w_1 + w_2 + w_3} \tag{A.2}$$

where w_1, w_2 and w_3 are weights you can assign (on the 0 to 1 scale) for the performance criteria A-1, A-2 and A-3, respectively. The total of all weights should equal 1.

A.2.5 Course Score for outcome A

The assessment workbook [1] incorporates the simple average approach as shown in Figure A.3.



K	L	M	N	O	P	Q	R
ns	Beam and Ball Pre-Lab Questions			Overall Pre-Lab Questions			
A-3	A-1	A-2	A-3	A-1	A-2	A-3	
6	8	14	6	3.40	3.31	3.43	
8	7	12	8	3.00	3.08	3.86	
8	8	10	8	2.40	3.69	3.00	
6	6	8	6	3.20	3.38	2.29	
4	6	14	4	3.60	2.92	2.29	
8	7	16	8	3.60	4.00	3.43	
4	4	16	4	2.80	3.31	2.29	
7	5	16	7	2.20	4.00	3.71	
7	8	10	7	3.20	3.08	3.43	
8	6	12	8	3.00	3.00	3.57	
8	8	16	8	40	104	28	
3.30	3.25	3.20	3.30				
			Average	3.04	3.38	3.13	
			Std. Dev.	0.47	0.40	0.62	
			SCORE for A:	3.18			

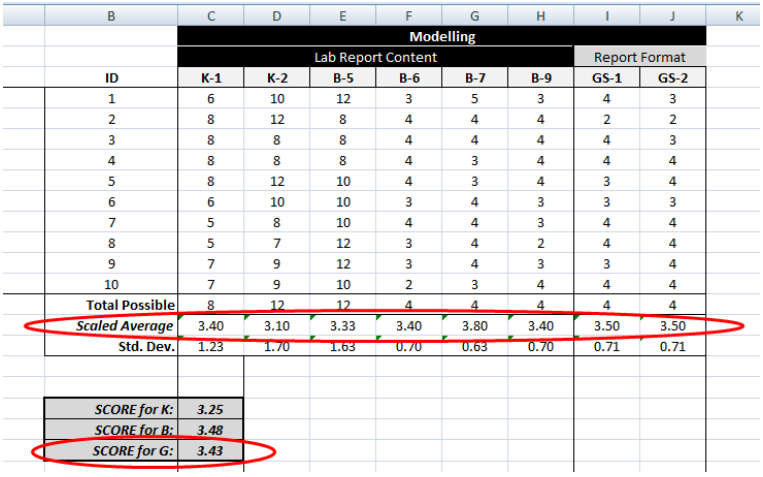
Figure A.3: Computation of single score for outcome ``A" in the assessment workbook.

A.2.6 Course Scores for outcomes B, K and G

Similarly, the simple average approach is also used for outcomes B, K and G. Referring to the rubrics in Section A.3, it should be noted that outcome ``G" contains performance criteria for both ``B" and ``K" to assess the *content* of the report. In addition, there are two performance criteria, GS-1 and GS-2, to assess the *format* of the report. The scores for all of these performance criteria are averaged to arrive at the single score for outcome G. For example, the single score for outcome G in Figure A.4 for the *Modelling* experiment was calculated using:

$$SCORE_G = AVERAGE(S_{K-1} + S_{K-2} + S_{B-5} + S_{B-6} + S_{B-7} + S_{B-9} + S_{GS-1} + S_{GS-2}) \quad \text{(A.3)}$$

where $S_{K-1} \cdots S_{GS-2}$ are the scaled average scores for K-1 through GS-2 in the workbook.



B	C	D	E	F	G	H	I	J	K
	Modelling								
	Lab Report Content						Report Format		
ID	K-1	K-2	B-5	B-6	B-7	B-9	GS-1	GS-2	
1	6	10	12	3	5	3	4	3	
2	8	12	8	4	4	4	2	2	
3	8	8	8	4	4	4	4	3	
4	8	8	8	4	3	4	4	4	
5	8	12	10	4	3	4	3	4	
6	6	10	10	3	4	3	3	3	
7	5	8	10	4	4	3	4	4	
8	5	7	12	3	4	2	4	4	
9	7	9	12	3	4	3	3	4	
10	7	9	10	2	3	4	4	4	
Total Possible	8	12	12	4	4	4	4	4	
Scaled Average	3.40	3.10	3.33	3.40	3.80	3.40	3.50	3.50	
Std. Dev.	1.23	1.70	1.63	0.70	0.63	0.70	0.71	0.71	
SCORE for K:	3.25								
SCORE for B:	3.48								
SCORE for G:	3.43								

Figure A.4: Computation of single score for outcome ``G" in the assessment workbook.

A.2.7 Assessment workbook

The *assessment workbook* [1] was developed using Microsoft Excel® . It is intented to give a general idea for how the assessment scores can be tracked and brought together. On purpose we designed the workbook to have no automatic features. You can use it as is or customize it in any way you like.

The assessment workbook has a tab for the Pre-Lab Questions and a tab for each of the laboratory chapters. Only 10 students were listed assuming you would use samples of student work and not the entire class. If you want to add more students, you can insert rows into the spreadsheets. **Note:** *If you insert new rows, make sure that the formula ranges in the cells with calculations are correct.*

At the bottom of each pre-lab section, there is a row entitled ``Total Possible". To count a pre-lab assignment in the calculation of the overall scores, you need to enter the correct totals here. For example, to count the Pre-Lab for modeling, you need to enter 12, 44 and 8 (Figure A.1). If you want to exclude an assignment from the overall calculation, enter ``0" as shown in Figure A.5. Of course, if you are excluding a pre-lab, then do not enter any scores for the students under those columns.

K	L	M	N	O	P	Q
	Beam and Ball Pre-Lab Questions			Overall Pre-Lab Questions		
ns A-3	A-1	A-2	A-3	A-1	A-2	A-3
6				3.25	3.27	3.60
8				2.88	3.09	3.80
8				2.00	3.91	2.60
6				3.25	3.64	2.00
4				3.75	2.82	2.40
8				3.63	4.00	3.20
4				3.00	3.18	2.40
7				2.13	4.00	3.80
7				3.00	3.18	3.40
8				3.00	3.00	3.40
8	0	0	0	32	88	20
3.30						
			Average	2.99	3.41	3.06
			Std. Dev.	0.56	0.44	0.65
		SCORE for A:		3.15		

Figure A.5: Enter ``0" to exclude or ``correct totals" to include a Pre-Lab assignment in the calculation of the overall scores.

A.3 Rubrics

	Code	Perf. Criteria	4 Exemplary	3 Proficient	2 Developing	1 Beginning or incomplete
Apply math, science and engineering	**A-1**	Has strategies to solve the problem	Uses a sophisticated strategy. Employs refined and complex reasoning to arrive at the solution.	Uses an appropriate strategy for solution. Content knowledge is used correctly.	Has a strategy for solution but content knowledge has some conceptual errors.	Uses a wrong strategy or there is no evidence of a strategy. Content knowledge has many errors.
	A-2	Performs calculations	Arrived at correct answer. Calculations are complete. Precise math language, symbolic notation, graphs diagrams, etc. are used.	Arrived at correct answer with correct calculations.	Arrived at correct answer. Calculations are mostly correct but there are some minor errors.	No answer or arrived at wrong answer. Calculations are mostly or completely wrong.
	A-3	Explains results	Explains the result in the context of the completed calculations by providing complex reasoning and interpretations. Clear logical conclusions are drawn.	Explains the result in the context of the completed calculations. Logical conclusions are drawn.	Some explanation of the result is provided but it does not demonstrate logical reasoning.	There are no explanations of the result or an attempt was made to provide an explanation but it is incomplete or wrong.

Table 6: **OUTCOME A**: An ability to apply knowledge of mathematics, science, and engineering

	Code	Perf. Criteria	4 Exemplary	3 Proficient	2 Developing	1 Beginning or incomplete
Design	**B-1**	Identifies hypothesis to test	Framed a testable question correctly and explained the anticipated cause-and-effect expectation leading to the question	Framed a testable question correctly	Framed a question that may or may not be testable	Incomplete or no testable question
	B-2	Identifies independent and dependent variables	All variables are identified correctly, explanations about their relations are provided	All variables are identified correctly	Most variables are identified correctly	None or only a few variables are identified correctly
	B-3	Lists assumptions made	All assumptions and their reasons are clearly listed	All assumptions are listed	Assumptions are listed but some are missing	No assumptions listed or most of them are missing
	B-4	Formulates experimental plan to investigate a phenomenon	Developed a sophisticated experimental procedure complete with details of every step to test the hypothesis	Developed correct experimental procedure to test the hypothesis	Attempted but could not completely develop an experimental procedure to test the hypothesis	Could not develop an accurate experimental procedure

(Continued on the next page)

	Code	Perf. Criteria	4 Exemplary	3 Proficient	2 Developing	1 Beginning or incomplete
Conduct	**B-5**	Follows experimental procedures	Follows experimental procedures carefully with great attention to detail. Makes precise measurements	Follows experimental procedures leading to correct measurements	Follows experimental procedures with some mistakes leading to mostly correct measurements	Follows experimental procedures with many mistakes leading to mostly wrong measurements
	B-6	Documents data collected	Systematically documents all data in an exemplary way and by using accurate units	Documents all data and with accurate units.	Documents data with some mistakes in the units or some data missing. Data organization needs improvement	No data are documented or there are major mistakes in the units
Analyze	**B-7**	Uses appropriate methods to analyze data	Excellent, in-depth analysis of the data using appropriate methods	Appropriate level of analysis of data using correct methods	Some data analysis but incomplete	No analysis or attempts to analyze with wrong methods
	B-8	Accounts for experimental uncertainties	Is aware of all potential experimental errors and can fully account for them with suggestions to improve them	Is aware of all potential experimental errors	Is aware of some of the potential experimental errors	Is unaware of any experimental errors
Interpret	**B-9**	Interprets results with respect to the original hypothesis	Provides clear, in-depth, accurate explanations, including trends, and arrives at logical conclusions based on data and results	Provides accurate explanations and logical conclusions based on data and results	Provides explanations and conclusions but with some errors	No explanation or conclusions are provided or they are wrong

Table 7: **OUTCOME B**: An ability to design and conduct experiments, as well as to analyze and interpret data.

	Code	Perf. Criteria	4 Exemplary	3 Proficient	2 Developing	1 Beginning or incomplete
Procedure	**B-1**	Identifies hypothesis to test	Framed a testable question correctly and explained the anticipated cause-and-effect expectation leading to the question	Framed a testable question correctly	Framed a question that may or may not be testable	Incomplete or no testable question
	B-2	Identifies independent and dependent variables	All variables are identified correctly, explanations about their relations are provided	All variables are identified correctly	Most variables are identified correctly	None or only a few variables are identified correctly
	B-3	Lists assumptions made	All assumptions and their reasons are clearly listed	All assumptions are listed	Assumptions are listed but some are missing	No assumptions listed or most of them are missing
	B-4	Formulates experimental plan to investigate a phenomenon	Developed a sophisticated experimental procedure complete with details of every step to test the hypothesis	Developed correct experimental procedure to test the hypothesis	Attempted but could not completely develop an experimental procedure to test the hypothesis Could not develop an accurate experimental procedure	
	B-5	Follows experimental procedures	Follows experimental procedures carefully with great attention to detail. Makes precise measurements	Follows experimental procedures leading to correct measurements	Follows experimental procedures with some mistakes leading to mostly correct measurements	Follows experimental procedures with many mistakes leading to mostly wrong measurements

(Continued on the next page)

	Code	Perf. Criteria	4 Exemplary	3 Proficient	2 Developing	1 Beginning or incomplete
Results	**B-6**	Documents data collected	Systematically documents all data in an exemplary way and by using accurate units	Documents all data and with accurate units.	Documents data with some mistakes in the units or some data missing. Data organization needs improvement	No data are documented or there are major mistakes in the units
	K-2	Uses software tools to present data in useful format (graphs, numerical, table, charts, diagrams)	Can use various software tools and their advanced features correctly for data presentation	Can use software tools correctly for data presentation	Can use software tools for data presentation with only a few mistakes	Cannot use software tools for data presentation or attempts to use them but with many mistakes (missing labels, etc.)
	K-3	Uses software tools to simulate physical systems	Can use software tools and their advanced features correctly for simulation	Can use software tools correctly for simulation	Can use software tools for simulation with only a few mistakes	Cannot use software tools for simulation or attempts to use them but with many mistakes
Analysis	**B-7**	Uses appropriate methods to analyze data	Excellent, in-depth analysis of the data using appropriate methods	Appropriate level of analysis of data using correct methods	Some data analysis but incomplete	No analysis or attempts to analyze with wrong methods
	B-8	Accounts for experimental uncertainties	Is aware of all potential experimental errors and can fully account for them with suggestions to improve them	Is aware of all potential experimental errors	Is aware of some of the potential experimental errors	Is unaware of any experimental errors
	K-1	Uses software tools for analysis	Can use various software tools and their advanced features correctly for analysis	Can use software tools correctly for analysis	Can use software tools for analysis with only a few mistakes	Cannot use software tools for analysis or attempts to use them but with many mistakes
Conclusions	**B-9**	Interprets results with respect to the original hypothesis	Provides clear, in-depth, accurate explanations, including trends, and arrives at logical conclusions based on data and results	Provides accurate explanations and logical conclusions based on data and results	Provides explanations and conclusions but with some errors	No explanation or conclusions are provided or they are wrong

Table 8: **OUTCOME G**: Ability to communicate effectively. (for Lab Report - **CONTENT**)

Code	Perf. Criteria	4 Exemplary	3 Proficient	2 Developing	1 Beginning or incomplete
GS-1	Content presentation well organized	• Each of the required sections is completed. • If necessary, subsections are used • All necessary background principles and information for the experiment are given • All grammar/spelling correct • References are cited	Two of the conditions for the "exemplary" category were not met	Three of the conditions for the "exemplary" category were not met	Four or none of the conditions for the "exemplary" category were not met
GS-2	Professional appearance	• Has cover page with all necessary details (title, course, student name(s), etc.) • Typed • Report layout is neat • Does not exceed specified maximum page limit • Pages are numbered • Equations are consecutively numbered • Figures are numbered, axes have labels, each figure has a descriptive caption • Tables are numbered, they include labels, each table has a descriptive caption • No hand drawn sketches/diagrams • References are cited using correct format	Two of the conditions for the "exemplary" category were not met	Four of the conditions for the "exemplary" category were not met	Five or more of the conditions for the "exemplary" category were not met

Table 9: **OUTCOME G**: Ability to communicate effectively. (for Lab Report - **FORMAT**)

	Code	Perf. Criteria	4 Exemplary	3 Proficient	2 Developing	1 Beginning or incomplete
Use techniques, skills and modern eng. tools	**K-1**	Uses software tools for analysis	Can use various software tools and their advanced features correctly for analysis	Can use software tools correctly for analysis	Can use software tools for analysis with only a few mistakes	Cannot use software tools for analysis or attempts to use them but with many mistakes
	K-2	Uses software tools to present data in useful format (graphs, numerical, table, charts, diagrams)	Can use various software tools and their advanced features correctly for data presentation	Can use software tools correctly for data presentation	Can use software tools for data presentation with only a few mistakes	Cannot use software tools for data presentation or attempts to use them but with many mistakes (missing labels, etc.)
	K-3	Uses software tools to simulate physical systems	Can use software tools and their advanced features correctly for simulation	Can use software tools correctly for simulation	Can use software tools for simulation with only a few mistakes	Cannot use software tools for simulation or attempts to use them but with many mistakes

Table 10: **OUTCOME K**: An ability to use the techniques, skills, and modern engineering tools necessary for engineering practice

References

[1] Quanser Inc. Qnet assessment workbook microsoft excel file, 2011.

[2] Quanser Inc. *QNET Rotary Pendulum Control Trainer User Manual*, 2011.

Six QNET Trainers to teach introductory controls using NI ELVIS

QNET DC Motor Control Trainer
teaches fundamentals of DC motor control

QNET HVAC Trainer
teaches temperature (process) control

QNET Mechatronic Sensors Trainer
teaches functions of 10 different sensors

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